

DRILLING OF HIGH-PERFORMANCE MATERIALS: EXPERIMENTAL, NUMERICAL,
AND THEORETICAL INVESTIGATIONS

by

WEILONG CONG

B.S., Dalian Fisheries University, 2007

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Industrial & Manufacturing Systems Engineering
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2013

Abstract

High-performance materials, such as silicon, aerospace stainless steels, titanium alloys, and carbon fiber reinforced plastic (CFRP) composites, have a variety of engineering applications. However, they usually have poor machinability and are classified as hard-to-machine materials. Drilling is one of the important machining processes for these materials. Industries are always under tremendous pressure to meet the ever-increasing demand for lower cost and better quality of the products made from these high-performance materials.

Rotary ultrasonic machining (RUM) is a non-traditional machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining. It is a relatively low-cost, environment-benign process that easily fits in the infrastructure of the traditional machining environment. Other advantages of this process include high hole accuracy, superior surface finish, high material removal rate, low tool pressure, and low tool wear rate.

The goal of this research is to provide new knowledge of machining these high performance materials with RUM for further improvement in the machined hole quality and decrease in the machining cost. A thorough research in this dissertation has been conducted by experimental, numerical, and theoretical investigations on output variables, including cutting force, torque, surface roughness, tool wear, cutting temperature, material removal rate, edge chipping (for silicon), power consumption (for CFRP), delamination (for CFRP), and feasible regions (for dry machining of CFRP). In this dissertation, an introduction of workpiece materials and RUM are discussed first. After that, two literature reviews on silicon drilling and dry drilling are presented. Then, design of experiment and finite element analysis on edge chipping in RUM of silicon, experimental investigations and finite element analysis on RUM of aerospace stainless steels, an ultrasonic vibration amplitude measurement method and a cutting temperature

measurement method for RUM using titanium alloys as workpiece, experimental and theoretical investigations on RUM of CFRP composites, and experimental studies on CFRP/Ti stacks are presented, respectively. Finally, conclusions and contributions on RUM drilling are discussed.

DRILLING OF HIGH-PERFORMANCE MATERIALS: EXPERIMENTAL, NUMERICAL,
AND THEORETICAL INVESTIGATIONS

by

WEILONG CONG

B.S., Dalian Fisheries University, 2007

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Industrial & Manufacturing Systems Engineering
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2013

Approved by:
Major Professor
Dr. Zhijian Pei

Copyright

WEILONG CONG

2013

Abstract

High-performance materials, such as silicon, aerospace stainless steels, titanium alloys, and carbon fiber reinforced plastic (CFRP) composites, have a variety of engineering applications. However, they usually have poor machinability and are classified as hard-to-machine materials. Drilling is one of the important machining processes for these materials. Industries are always under tremendous pressure to meet the ever-increasing demand for lower cost and better quality of the products made from these high-performance materials.

Rotary ultrasonic machining (RUM) is a non-traditional machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining. It is a relatively low-cost, environment-benign process that easily fits in the infrastructure of the traditional machining environment. Other advantages of this process include high hole accuracy, superior surface finish, high material removal rate, low tool pressure, and low tool wear rate.

The goal of this research is to provide new knowledge of machining these high performance materials with RUM for further improvement in the machined hole quality and decrease in the machining cost. A thorough research in this dissertation has been conducted by experimental, numerical, and theoretical investigations on output variables, including cutting force, torque, surface roughness, tool wear, cutting temperature, material removal rate, edge chipping (for silicon), power consumption (for CFRP), delamination (for CFRP), and feasible regions (for dry machining of CFRP). In this dissertation, an introduction of workpiece materials and RUM are discussed first. After that, two literature reviews on silicon drilling and dry drilling are presented. Then, design of experiment and finite element analysis on edge chipping in RUM of silicon, experimental investigations and finite element analysis on RUM of aerospace stainless steels, an ultrasonic vibration amplitude measurement method and a cutting temperature

measurement method for RUM using titanium alloys as workpiece, experimental and theoretical investigations on RUM of CFRP composites, and experimental studies on CFRP/Ti stacks are presented, respectively. Finally, conclusions and contributions on RUM drilling are discussed.

Table of Contents

Table of Contents	viii
List of Figures	xxiii
List of Tables	xxxvi
Acknowledgements	xxxix
Dedication	xl
Chapter 1 - Introduction	1
1.1 Introduction of high-performance materials and their drilling methods	1
1.1.1 Silicon	1
1.1.2 Aerospace stainless steels	2
1.1.3 Titanium alloys	3
1.1.4 Carbon fiber reinforced plastic (CFRP) composites	3
1.2 Introduction of rotary ultrasonic machining	5
1.3 Structures and objectives of this research	6
References	7
Chapter 2 - Literature Review – Silicon Drilling	16
Abstract	17
2.1 Introduction	17
2.2 Laser drilling	19
2.2.1 Principle of laser drilling	19
2.2.2 Characteristics of laser drilling	20
2.2.3 Laser drilling system set-up	21

2.2.4 Experimental investigations	21
2.3 Microwave drilling	22
2.3.1 Principle of microwave drilling	22
2.3.2 Characteristics of microwave drilling	23
2.3.3 Microwave drilling system set-up	24
2.4 Electro-discharge machining (EDM)	24
2.4.1 Principle of electro-discharge machining	24
2.4.2 Characteristics of electro-discharge machining	25
2.4.3 Electro-discharge machining system set-up	25
2.4.4 Experimental investigations	26
2.5 Ultrasonic vibration assisted drilling	27
2.5.1 Principle of ultrasonic vibration assisted drilling	27
2.5.2 Characteristics of ultrasonic vibration assisted drilling	27
2.5.3 Ultrasonic vibration assisted drilling system set-up	27
2.5.4 Experimental investigations	28
2.6 Rotary ultrasonic machining (RUM)	29
2.6.1 Principle of rotary ultrasonic machining	29
2.6.2 Characteristics of rotary ultrasonic machining	30
2.6.3 Rotary ultrasonic machining system set-up	30
2.6.4 Experimental investigations	30
2.7 Conclusion remarks	31
References	32
Chapter 3 - Literature Review - Dry Machining	37

3.1 Introduction.....	38
3.2 Effects on cutting forces	40
3.3 Effects on cutting temperature	42
3.4 Effects on tool wear	44
3.5 Effects on surface roughness	49
3.6 Effects on residual stress.....	53
3.7 Concluding remarks.....	56
References.....	56
Chapter 4 - Silicon – A Study on Edge Chipping.....	59
Abstract.....	60
4.1 Introduction.....	60
4.2 Experimental conditions and procedure	63
4.2.1 Experimental conditions	63
4.2.2 Design of experiments	66
4.2.3 Measurement procedures	67
4.3 Experimental results	69
4.3.1 Main effects on edge chipping.....	69
4.3.2 Main effects on cutting force	72
4.3.3 Interaction effects on cutting force	74
4.3.4 Relationships between cutting force and edge chipping.....	76
4.4 FEA simulation on edge chipping	77
4.4.1 Failure criterion of edge chipping.....	77
4.4.2 The FEA model.....	78

4.4.3 Simulation Results	79
4.5 Conclusions.....	80
Acknowledgments	80
References.....	80
Chapter 5 - Aerospace Stainless Steel - Feasibility Study	88
Abstract.....	89
5.1 Introduction.....	89
5.2 Experimental conditions and procedure	91
5.2.1 Experimental conditions	91
5.2.2 Measurement procedure.....	94
5.3 Results and discussion	95
5.3.1 Effects on cutting force	95
5.3.2 Effects on torque	99
5.3.3 Effects on surface roughness.....	101
5.4 Conclusions.....	105
Acknowledgments	106
References.....	106
Chapter 6 - Aerospace Stainless Steel - Comparison of Superabrasive Tools	114
Abstract.....	115
6.1 Introduction.....	115
6.2 Experimental conditions and procedures	117
6.2.1 Experimental set-up and conditions	117
6.2.2 Measurement procedure.....	120

6.3 Comparison of tool wear.....	122
6.4 Comparison of cutting force	124
6.5 Comparison of torque	125
6.6 Comparison of surface roughness.....	126
6.7 Conclusions.....	127
Acknowledgements.....	128
References.....	128
Chapter 7 - Aerospace Stainless Steel - Design of Experiments on Cutting Force and Torque.	132
Abstract.....	133
7.1 Introduction.....	133
7.2 Experimental set-up and procedure	135
7.2.1 Experimental conditions	135
7.2.2 Design of experiment.....	136
7.2.3 Measurement procedure.....	138
7.3 Results of designed experiments.....	138
7.3.1 Main effects on cutting force	138
7.3.2 Two-factor interactions on cutting force.....	140
7.3.3 Three-factor interaction on cutting force	141
7.3.4 Main effects on torque	141
7.3.5 Two-factor interactions on torque.....	142
7.3.6 Three-factor interaction on torque	144
7.4 Conclusions.....	144
Acknowledgements.....	145

References.....	145
Chapter 8 - Aerospace Stainless Steel - Design of Experiment on Surface Roughness	150
Abstract.....	151
8.1 Introduction.....	151
8.2 Experiment set-up and procedure	153
8.3 Results and discussion	155
8.3.1 Main effects on surface roughness at the entrance	156
8.3.2 Two-factor interactions on surface roughness at the entrance.....	156
8.3.3 Three-factor interactions on surface roughness at the entrance.....	157
8.3.4 Main effects on surface roughness at the exit.....	158
8.3.5 Two-factor interactions on surface roughness at the exit	159
8.3.6 Three-factor interactions on surface roughness at the exit	160
8.4 Conclusions.....	161
Acknowledgements.....	162
References.....	162
Chapter 9 - Aerospace Stainless Steel - Hypotheses about Surface Roughness.....	164
Abstract.....	165
9.1 Introduction.....	165
9.2 Hypothesis 1	168
9.2.1 Hypothesis.....	168
9.2.2 Hypothesis testing via experiments	169
9.3 Hypothesis 2	175
9.3.1 Hypothesis.....	175

9.3.2 Hypothesis testing via simulations.....	176
9.4 Hypothesis 3	179
9.4.1 Hypothesis.....	179
9.4.2 Hypothesis testing via experiments	179
9.5 Conclusions.....	182
Acknowledgments	183
References.....	183
Chapter 10 - Titanium alloy - A Novel Measurement Method for Vibration Amplitude.....	186
Abstract.....	187
10.1 Introduction.....	187
10.2 The novel measurement method, the dial indicator method, and other experimental conditions.....	190
10.2.1 The novel measurement method	190
10.2.2 The dial indicator method	191
10.2.3 Other experiment conditions.....	192
10.3 Experimental results and discussion	194
10.3.1 Effects of cutting tool on vibration amplitude	194
10.3.2 Effects of ultrasonic power on vibration amplitude.....	197
10.3.3 Effects of workpiece material on vibration amplitude.....	198
10.3.4 Effects of tool rotation speed on vibration amplitude.....	199
10.3.5 Effects of feedrate on vibration amplitude.....	200
10.4 Conclusions.....	200
Acknowledgments	201

References.....	202
Chapter 11 - Titanium alloy - A Study on Cutting Temperature	206
Abstract.....	207
11.1 Introduction.....	207
11.2 Experimental conditions and measurement procedures.....	209
11.2.1 Experimental set-up	209
11.2.2 Experimental conditions	210
11.2.3 Experimental procedures.....	211
11.3 Experimental results	214
11.3.1 Effects of ultrasonic power	214
11.3.2 Effects of tool rotation speed	215
11.3.3 Effects of feedrate	216
11.3.4 Effects of outer coolant.....	217
11.3.5 Effects of coolant pressure.....	218
11.3.6 Effects of coolant flow rate.....	218
11.4 Conclusions.....	219
Acknowledgements.....	220
References.....	220
Chapter 12 - CFRP - Feasibility Study	225
Abstract.....	226
12.1 Introduction.....	226
12.2 Experimental conditions and measurement procedures.....	228
12.2.1 Properties of workpiece material	228

12.2.2 Experimental set-up	229
12.2.3 Experimental conditions	231
12.2.4 Measurement procedures for output variables	232
12.3 Experimental results	235
12.3.1 Cutting force	235
12.3.2 Torque	236
12.3.3 Surface roughness	238
12.3.4 Delamination	240
12.3.5 Tool life	241
12.3.6 Material removal rate (MRR)	242
12.4 Conclusions	244
Acknowledgements	245
References	245
Chapter 13 - CFRP - Dry Drilling	250
Abstract	251
13.1 Introduction	251
13.2 Experimental conditions and measurement procedures	253
13.3 Experimental results	258
13.3.1 Results on cutting force	258
13.3.2 Results on torque	260
13.3.3 Results on surface roughness	263
13.3.4 Results on burning of machined surface	267
13.3.5 Results on tool wear	268

13.4 Conclusions.....	269
Acknowledgements.....	269
References.....	270
Chapter 14 - CFRP - Feasible Regions in Dry Drilling	275
Abstract.....	276
14.1 Introduction.....	276
14.2 Experimental conditions and evaluation criteria	279
14.2.1 Experimental set-up	279
14.2.2 Workpiece size and material properties	282
14.2.3 Experimental conditions	283
14.2.4 Criteria of feasible regions	284
14.3 Experimental results	286
14.3.1 Feasible regions of tool rotation speed and feedrate.....	286
14.3.2 Feasible regions of ultrasonic power and feedrate.....	287
14.3.3 Feasible regions of tool rotation speed and ultrasonic power.....	288
14.4 Conclusions.....	290
Acknowledgements.....	290
References.....	291
Chapter 15 - CFRP - A Study on Power Consumption	295
Abstract.....	296
15.1 Introduction.....	296
15.2 Experimental conditions	298
15.2.1 Workpiece material properties	298

15.2.2 Experimental set-up	300
15.2.3 Measurement procedures	304
15.3 Results and discussion	306
15.3.1 Effects of ultrasonic power	306
15.3.2 Effects of tool rotation speed	311
15.3.3 Effects of feedrate	314
15.3.4 Effects of CFRP type	317
15.4 Conclusions.....	319
Acknowledgements.....	321
References.....	321
Chapter 16 - CFRP - A Study on Cutting Temperature.....	324
Abstract.....	325
16.1 Introduction.....	325
16.2 Experimental set-up and conditions.....	328
16.2.1 Workpiece	328
16.2.2 Experimental set-up	329
16.2.3 Measurement procedure.....	332
16.3 Results and discussion	335
16.3.1 Effects of ultrasonic power	335
16.3.2 Effects of tool rotation speed	338
16.3.3 Effects of feedrate	341
16.4 Conclusions.....	343
Acknowledgements.....	344

References.....	344
Chapter 17 - CFRP - A Mechanistic Predictive Model on Cutting Force	348
Abstract.....	349
17.1 Introduction.....	350
17.1.1 Introduction of carbon fiber reinforced plastic (CFRP) composites.....	350
17.1.2 Introduction of rotary ultrasonic machining	351
17.1.3 Reported investigations on RUM of CFRP	352
17.1.4 Purposes of the paper	352
17.2 Model development	353
17.2.1 Approach to model development	353
17.2.2 CFRP material removal mechanism analysis	354
17.2.3 Assumptions in model development.....	356
17.2.4 CFRP micromechanical analysis (strength of materials approach)	357
17.2.5 Relationship between indentation depth and maximum impact force	358
17.2.6 Elastic modulus and Poisson's ratio	359
17.2.7 Impulse, impact force, and cutting force	362
17.2.8 Material removal volume by one abrasive particle.....	363
17.2.9 Material removal rate	367
17.2.10 The cutting force model	368
17.3 Process of obtaining fracture volume factor (K_V).....	369
17.3.1 Methodology	369
17.3.2 Experimental set-up and conditions	369
17.3.3 Design of experiments	373

17.3.4 Analysis of K_v from experimental results	374
17.4 Predicted influences of input variables on cutting force.....	375
17.4.1 Predicted results on cutting force.....	377
17.4.2 Predicted results on important intermediate variables	377
17.5 Pilot experimental verification.....	384
17.6 Conclusions.....	386
Acknowledgements.....	387
References.....	387
Chapter 18 - CFRP/Ti Stacks - Feasibility Study	394
Abstract.....	395
18.1 Introduction.....	395
18.2 Experiments	398
18.2.1 Properties and size of CFRP/Ti stacks.....	398
18.2.2 Experimental set-up	400
18.2.3 Experimental conditions	402
18.2.4 Measurement procedures	403
18.3 Results and discussion	407
18.3.1 Cutting force	407
18.3.2 Torque	409
18.3.3 Surface roughness	410
18.3.4 CFRP groove depth.....	412
18.3.5 Ti exit burr	413
18.3.6 CFRP entrance delamination	414

18.3.7 Hole size variation	415
18.3.8 Tool life.....	417
18.4 Conclusions.....	417
Acknowledgements.....	418
References.....	418
Chapter 19 - CFRP/Ti Stacks - Effects of Two Feedrate Types.....	424
Abstract.....	425
19.1 Introduction.....	425
19.2 Experiments	427
19.2.1 Properties of workpiece materials.....	427
19.2.2 Experimental set-up	429
19.2.3 Experimental conditions	431
19.2.4 Measurement procedures	433
19.3 Results and discussion	435
19.3.1 Cycle time	435
19.3.2 Cutting force	436
19.3.3 Torque	438
19.3.4 Tool wear	439
19.3.5 Surface roughness	441
19.3.6 Groove depth.....	443
19.4 Conclusions.....	445
Acknowledgements.....	446
References.....	446

Chapter 20 - Conclusions and contributions	452
20.1 Conclusions	452
20.2 Contributions of this dissertation	455
Appendix A - Publications during Ph.D. study	457
Journals and transactions	457
Proceedings	460
Submitted papers	463
Posters	464

List of Figures

Figure 1.1 Illustration of rotary ultrasonic machining.	5
Figure 2.1 Illustrations of solar panel structures (after [6-9]).....	18
Figure 2.2 Schematic illustration of laser drilling (after [14,15]).....	20
Figure 2.3 Several methods of laser drilling (after [15,16]).	20
Figure 2.4 Schematic diagram of a laser drilling system (after [15]).	21
Figure 2.5 Illustration of microwave drilling (after [26]).....	23
Figure 2.6 Schematic illustration of EDM (after [27,28]).	25
Figure 2.7 Illustration of EDM tool electrode (after [29]).....	25
Figure 2.8 Schematic illustration of a typical EDM system (after [27,28]).	26
Figure 2.9 Illustration of ultrasonic vibration assisted drilling (after [33]).	28
Figure 2.10 Illustration of rotary ultrasonic machining (after [34]).	29
Figure 2.11 System set-up of rotary ultrasonic machining (after [34]).	31
Figure 3.1 Costs in machining (after [2]).....	38
Figure 3.2 Vortex tube (after [7]).	39
Figure 3.3 Tangential grinding force (after [11]).....	42
Figure 3.4 Normal grinding force (after [11]).	42
Figure 3.5 Cutting temperature under different coolant conditions (after [13]).	44
Figure 3.6 Tool wear under different cooling conditions (after [12]).....	45
Figure 3.7 Tool wear with and without VT cooling (after [14]).....	46
Figure 3.8 Relationship between tool wear and cutting time (after [14]).....	46
Figure 3.9 Nose wear curves when turning of Inconel 718 (after [15]).	48
Figure 3.10 Max flank wear curves when milling of tool steel AISI D2 (after [15]).....	48

Figure 3.11 Surface roughness when turning of Inconel 718 (after [15]).	49
Figure 3.12 Surface roughness when milling of tool steel AISI D2 (after [15]).	50
Figure 3.13 Surface roughness when grinding of tool steel (after [11]).	51
Figure 3.14 Surface roughness with VT cooling and coolant fluid when grinding of spindle shaft material (depth of cut was 10 μm) (after [16]).	52
Figure 3.15 Surface roughness under different VT cooling conditions when grinding of spindle shaft material (depth of cut was 10 μm) (after [16]).	52
Figure 3.16 Longitudinal residual stress (after [11]).	53
Figure 3.17 Transverse residual stress (after [11]).	54
Figure 3.18 Residual stress when grinding of SCM4 (after [16]).	55
Figure 3.19 Residual stress when grinding of SCM21 (after [16]).	55
Figure 4.1 Illustration of RUM of silicon.	63
Figure 4.2 Experimental set-up.	64
Figure 4.3 Illustration of RUM tool.	65
Figure 4.4 Fixing of silicon workpiece.	66
Figure 4.5 Illustration of edge chipping.	67
Figure 4.6 Typical relationship between cutting force and time	68
Figure 4.7 Main effect of tool rotation speed on edge chipping.	71
Figure 4.8 Main effect of ultrasonic power on edge chipping.	71
Figure 4.9 Main effect of feedrate on edge chipping.	71
Figure 4.10 Main effect of tool rotation speed on cutting force.	73
Figure 4.11 Main effect of ultrasonic power on cutting force.	73
Figure 4.12 Main effect of feedrate on cutting force.	73

Figure 4.13 Interaction effects between ultrasonic power and tool rotation speed on cutting force.	75
Figure 4.14 Interaction effects between feedrate and tool rotation speed on cutting force.	75
Figure 4.15 Interaction effects between feedrate and ultrasonic power on cutting force.	75
Figure 4.16 Three-factor interaction effects on cutting force.	76
Figure 4.17 Relationships between cutting force and edge chipping.	77
Figure 4.18 Finite element analysis model of RUM of silicon.	79
Figure 5.1 Illustration of rotary ultrasonic machining.	91
Figure 5.2 Experimental set-up.	92
Figure 5.3 Measurement of surface roughness.	95
Figure 5.4 Effects of spindle speed on cutting force.	96
Figure 5.5 Effects of feedrate on cutting force.	97
Figure 5.6 Effects of ultrasonic power on cutting force.	98
Figure 5.7 Effects of spindle speed on torque.	99
Figure 5.8 Effects of feedrate on torque.	100
Figure 5.9 Effects of ultrasonic power on torque.	101
Figure 5.10 Effects of spindle speed on surface roughness measured at the entrance location.	102
Figure 5.11 Effects of spindle speed on surface roughness measured at the exit location.	102
Figure 5.12 Effects of feedrate on surface roughness measured at the entrance location.	103
Figure 5.13 Effects of feedrate on surface roughness measured at the exit location.	103
Figure 5.14 Effects of ultrasonic power on surface roughness measured at the entrance location.	104
Figure 5.15 Effects of ultrasonic power on surface roughness measured at the exit location.	105

Figure 6.1 Illustration of RUM.	116
Figure 6.2 Experimental set-up.....	118
Figure 6.3 Illustration of RUM tool.....	119
Figure 6.4 Schematic illustration of cutting force measurement.	121
Figure 6.5 Illustration of surface roughness measurement.	122
Figure 6.6 Illustration of wear mechanism for fixed abrasive tools (after[19-22]).	122
Figure 6.7 Attritious wear on end faces of CBN and diamond tool.	123
Figure 6.8 Fracture wear on the end faces of CBN tool.	124
Figure 6.9 Cutting force versus cutting time.	125
Figure 6.10 Results on torque with CBN and diamond tools.	125
Figure 6.11 Effects on surface roughness of the machined hole.	126
Figure 6.12 Effects on surface roughness of the machined rod.	127
Figure 7.1 Illustration of RUM.	135
Figure 7.2 Experiment set-up.....	136
Figure 7.3 Main effects of spindle speed on cutting force.....	139
Figure 7.4 Main effects of ultrasonic power on cutting force.....	139
Figure 7.5 Main effects of feedrate on cutting force.	139
Figure 7.6 Interaction effects between spindle speed and ultrasonic power on cutting force. ...	140
Figure 7.7 Interaction effects between spindle speed and feedrate on cutting force.	141
Figure 7.8 Interaction effects between ultrasonic power and feedrate on cutting force.	141
Figure 7.9 Main effects of spindle speed on torque.....	142
Figure 7.10 Main effects of ultrasonic power on torque.....	142
Figure 7.11 Main effects of feedrate on torque.....	142

Figure 7.12 Interaction effects between spindle speed and ultrasonic power on torque.	143
Figure 7.13 Interaction effects between spindle speed and feedrate on torque.	143
Figure 7.14 Three-factor interaction effects on torque.	144
Figure 8.1 Illustration of rotary ultrasonic machining.	152
Figure 8.2 Experiment set-up.....	153
Figure 8.3 Measurement procedure for surface roughness.	155
Figure 8.4 Main effect on surface roughness at the entrance.	156
Figure 8.5 Two-factor interactions on surface roughness at the entrance.	157
Figure 8.6 Three-factor interactions on surface roughness at the entrance.	158
Figure 8.7 Main effects on surface roughness at exit location.	159
Figure 8.8 Two-factor interactions on surface roughness at the exit.	160
Figure 8.9 Three-factor interactions on surface roughness at the exit.	161
Figure 9.1 Illustration of RUM.	166
Figure 9.2 Illustration of the core drill.....	166
Figure 9.3 Illustration of entrance and exit sides of machined hole and rod.	167
Figure 9.4 Pictures of machined hole surface by RUM.....	168
Figure 9.5 Illustration of Hypothesis 1.	169
Figure 9.6 Experiment set-up.....	170
Figure 9.7 Illustration of Test 1 for Hypothesis 1.....	172
Figure 9.8 Experimental results of Test 1 for Hypothesis 1.	173
Figure 9.9 Illustration of Test 2 for Hypothesis 1.....	174
Figure 9.10 Experimental results of Test 2 for Hypothesis 1.	175
Figure 9.11 Illustration of Hypothesis 2.	176

Figure 9.12 Finite element analysis model of workpiece.	177
Figure 9.13 Dimensions of the tools used in experiments (unit: mm).	178
Figure 9.14 Illustration of Test for Hypothesis 3.	180
Figure 9.15 Experimental results of Test for Hypothesis 3.	181
Figure 9.16 Surface roughness results when drilling with RUM in standard fashion.	182
Figure 10.1 Illustration of rotary ultrasonic machining.	188
Figure 10.2 Measurement of vibration amplitude on a microscopic picture.	191
Figure 10.3 Measurement of vibration amplitude with the dial indicator method.	192
Figure 10.4 Five different tools used in this study.	193
Figure 10.5 Effects of cutting tool on vibration amplitude.	194
Figure 10.6 Effects of ultrasonic power on vibration amplitude (measure with the dial indicator method) for five tools (#1, #2, #3, #4, and #5).	195
Figure 10.7 Effects of ultrasonic power on vibration amplitude.	196
Figure 10.8 Effects of workpiece material on vibration amplitude.	198
Figure 10.9 Effects of tool rotation speed on vibration amplitude.	199
Figure 10.10 Effects of feedrate on vibration amplitude.	200
Figure 11.1 Illustration of rotary ultrasonic machining.	208
Figure 11.2 Experimental set-up.	209
Figure 11.3 Illustration of the tool.	210
Figure 11.4 Illustration of temperature measurement in RUM.	213
Figure 11.5 A typical curve of temperature versus machining time.	213
Figure 11.6 Effects of ultrasonic power on cutting temperature.	214
Figure 11.7 Effects of tool rotation speed on cutting temperature.	215

Figure 11.8 Effects of feedrate on cutting temperature.	216
Figure 11.9 Effects of outer coolant on cutting temperature.	217
Figure 11.10 Effects of coolant pressure on cutting temperature.	218
Figure 11.11 Effects of coolant flow rate on cutting temperature.	219
Figure 12.1 Illustration of two CFRP drilling processes.	227
Figure 12.2 Illustration of woven fabric in CFRP.	228
Figure 12.3 RUM experimental set-up.	230
Figure 12.4 Illustration of RUM tool.	230
Figure 12.5 Typical relationship between cutting force and time (in RUM).	232
Figure 12.6 Illustration of surface roughness measurement.	233
Figure 12.7 Measurement of delamination factor.	233
Figure 12.8 Illustration of the hole and rod machined by rotary ultrasonic machining.	234
Figure 12.9 Cutting force comparison between RUM and twist drilling when tool rotation speed changed.	235
Figure 12.10 Cutting force comparison between RUM and twist drilling when feedrate changed.	236
Figure 12.11 Torque comparison between RUM and twist drilling when tool rotation speed changed.	237
Figure 12.12 Torque comparison between RUM and twist drilling when feedrate changed.	238
Figure 12.13 Surface roughness comparison between RUM and twist drilling when tool rotation speed changed.	239
Figure 12.14 Surface roughness comparison between RUM and twist drilling when feedrate changed.	239

Figure 12.15 Effects of tool rotation speed on delamination factor in twist drilling.....	240
Figure 12.16 Effects of feedrate on delamination factor in twist drilling.....	241
Figure 12.17 A new RUM tool and a used RUM tool after drilling more than 200 holes.	242
Figure 12.18 A new twist drill and a used twist drill after drilling five holes.....	242
Figure 12.19 Material removal rate comparison between RUM and twist drilling when tool rotation speed changed.....	243
Figure 12.20 Material removal rate comparison between RUM and twist drilling when feedrate changed.	244
Figure 13.1 Experimental set-up.....	255
Figure 13.2 Comparison of cutting force under different settings of ultrasonic power.....	258
Figure 13.3 Comparison of cutting force under different settings of tool rotation speed.....	259
Figure 13.4 Comparison of cutting force under different settings of feedrate.....	260
Figure 13.5 Comparison of torque under different settings of ultrasonic power.....	261
Figure 13.6 Comparison of torque under different settings of tool rotation speed.....	262
Figure 13.7 Comparison of torque under different settings of feedrate.....	262
Figure 13.8 Comparison of surface roughness under different settings of ultrasonic power.	264
Figure 13.9 Comparison of surface roughness under different settings of tool rotation speed. .	265
Figure 13.10 Comparison of surface roughness under different settings of feedrate.	266
Figure 13.11 Comparison of tool wear.	268
Figure 14.1 Illustration of rotary ultrasonic machining.	278
Figure 14.2 Illustration of experimental set-up.....	280
Figure 14.3 Illustration of vortex tube (after [AiRTX, 2008; Hilsch, 1947; Cong et al., 2008]).	281

Figure 14.4 Illustration of a metal-bonded diamond core drill.	282
Figure 14.5 Illustration of CFRP.	283
Figure 14.6 Illustration of delamination.	285
Figure 14.7 Illustration of tool blockage.....	285
Figure 14.8 Feasible regions of tool rotation speed and feedrate.	286
Figure 14.9 Feasible regions of ultrasonic power and feedrate.	288
Figure 14.10 Feasible regions of tool rotation speed and ultrasonic power.	289
Figure 15.1 Illustration of rotary ultrasonic machining.	297
Figure 15.2 Fiber structures of CFRP.....	300
Figure 15.3 Illustration of experimental set-up.....	301
Figure 15.4 Illustration of the working cycle of the air compressor.....	302
Figure 15.5 Illustration of a metal-bonded diamond core drill.....	303
Figure 15.6 Relationship between ultrasonic power and amplitude.	304
Figure 15.7 Effects of ultrasonic power.....	307
Figure 15.8 Power consumption percentage of each component under different settings of ultrasonic power.	310
Figure 15.9 Effects of tool rotation speed.....	312
Figure 15.10 Power consumption percentage of each component under different settings of tool rotation speed.	313
Figure 15.11 Effects of feedrate.....	315
Figure 15.12 Power consumption percentage of each component under different settings of feedrate.....	316
Figure 15.13 Effects of CFRP type.....	318

Figure 15.14 Power consumption percentage of each component under different CFRP type..	319
Figure 16.1 Illustration of rotary ultrasonic machining.	326
Figure 16.2 Fiber structures of CFRP.	328
Figure 16.3 Illustration of experimental set-up.....	330
Figure 16.4 Illustration of a metal-bonded diamond core drill.	331
Figure 16.5 Illustration of temperature measurement.	333
Figure 16.6 The structure of the fiber optic sensor.	333
Figure 16.7 The relationship between wavelength and cutting temperature.	334
Figure 16.8 Cutting temperature versus machining time for different levels of ultrasonic power. (Tool rotation speed = 3000 rpm; Feedrate = 0.3 mm/s)	336
Figure 16.9 Effects of ultrasonic power on maximum cutting temperature. (Tool rotation speed = 3000 rpm; Feedrate = 0.3 mm/s).....	338
Figure 16.10 Cutting temperature versus machining time for different levels of tool rotation speed. (Feedrate = 0.3 mm/s; Ultrasonic power = 40%).....	339
Figure 16.11 Effects of tool rotation speed on maximum cutting temperature. (Feedrate = 0.3 mm/s; Ultrasonic power = 40%)	340
Figure 16.12 Cutting temperature versus machining time for different levels of feedrate. (Tool rotation speed = 3000 rpm; Ultrasonic power = 40%).....	342
Figure 16.13 Effects of feedrate on maximum cutting temperature. (Tool rotation speed = 3000 rpm; Ultrasonic power = 40%)	343
Figure 17.1 Illustration of RUM and microscope pictures of machined cylindrical surface, machined end surface, and cutting chips.	351
Figure 17.2 Input variables in development of RUM cutting force model for CFRP.	354

Figure 17.3 SEM pictures of machined surface.....	355
Figure 17.4 Micromechanics process (After [Barbero, 2010]).....	357
Figure 17.5 Cylindrical fiber simplification method.	360
Figure 17.6 Calculation of effective cutting time Δt (after [Pei et al., 1995b]).....	362
Figure 17.7 Cracks in brittle material induced by indentation of an abrasive grain [Lawn et al., 1980].	364
Figure 17.8 Theoretical volume of fracture zone.....	365
Figure 17.9 RUM system set-up.	370
Figure 17.10 Illustration of cutting tool.....	372
Figure 17.11 Calculation of K_v from experimental results.	375
Figure 17.12 Influence of input variables on K_v	376
Figure 17.13 Predicted results on cutting force under different input variables.....	378
Figure 17.14 Influences of ultrasonic vibration amplitude.....	379
Figure 17.15 Influences of tool rotation speed.	380
Figure 17.16 Influences of feedrate.	381
Figure 17.17 Influences of abrasive size.....	383
Figure 17.18 Influences of abrasive concentration.	384
Figure 17.19 Comparisons of predicted and experimental results.....	385
Figure 18.1 Illustration of rotary ultrasonic machining (RUM).	398
Figure 18.2 Illustration of woven fabric and CFRP structure.....	399
Figure 18.3 RUM experimental set-up.	401
Figure 18.4 Illustration of RUM tool.....	402
Figure 18.5 A typical cutting force and time curve.	404

Figure 18.6 Surface roughness and groove depth measurements.	405
Figure 18.7 Illustrations of Ti exit burr and burr height.	405
Figure 18.8 Measurement of delamination factor.	406
Figure 18.9 Comparison of cutting force.	409
Figure 18.10 Comparison of torque.	410
Figure 18.11 Comparison of surface roughness.	411
Figure 18.12 Comparison of CFRP groove depth.	412
Figure 18.13 Top view of Ti exit side of a hole drilled using RUM.	413
Figure 18.14 Comparison of Ti burr height.	413
Figure 18.15 Top view of CFRP entrance side of a hole drilled using RUM.	414
Figure 18.16 Comparison of CFRP entrance delamination.	414
Figure 18.17 Comparison of hole size variation.	416
Figure 18.18 Comparison of tool life.	417
Figure 19.1 Illustration of rotary ultrasonic machining.	426
Figure 19.2 Illustrations of woven fabric and CFRP structures.	428
Figure 19.3 RUM experimental set-up.	430
Figure 19.4 Illustration of RUM cutting tool.	430
Figure 19.5 Illustrations of fixed feedrate and variable feedrate.	432
Figure 19.6 Illustration of feeding depth.	432
Figure 19.7 Typical cutting force-time curves using fixed and variable feedrate.	434
Figure 19.8 Surface roughness and groove depth measurements.	435
Figure 19.9 Comparison of cycle time.	436

Figure 19.10 Comparison of cutting force at different levels of ultrasonic power. (Tool rotation speed = 4000 rpm)	437
Figure 19.11 Comparison of cutting force at different levels of tool rotation speed. (Ultrasonic power = 40%).....	437
Figure 19.12 Comparison of torque at different levels of ultrasonic power. (Tool rotation speed = 4000 rpm).....	438
Figure 19.13 Comparison of torque at different levels of tool rotation speed. (Ultrasonic power = 40%).....	439
Figure 19.14 Comparison of tool wear at different levels of ultrasonic power. (Tool rotation speed = 4000 rpm)	440
Figure 19.15 Comparison of tool wear at different levels of tool rotation speed. (Ultrasonic power = 40%).....	440
Figure 19.16 Comparison of surface roughness at different levels of ultrasonic power. (Tool rotation speed = 4000 rpm).....	442
Figure 19.17 Comparison of surface roughness at different levels of tool rotation speed. (Ultrasonic power = 40%).....	443
Figure 19.18 Comparison of groove depth at different levels of ultrasonic power. (Tool rotation speed = 4000 rpm)	444
Figure 19.19 Comparison of groove depth at different levels of tool rotation speed. (Ultrasonic power = 40%).....	444
Figure 20.1 Studies of this dissertation.....	452

List of Tables

Table 2.1 Summary of experimental investigations on laser drilling.	22
Table 2.2 Comparison of five drilling methods.	32
Table 2.3 Summary of reported experimental investigations on silicon drilling.	32
Table 3.1 Reported methods of dry machining.	39
Table 3.2 Experimental conditions used by Nguyen and Zhang [11].	41
Table 3.3 Cooling conditions used by Nguyen and Zhang [11].	41
Table 3.4 Experimental conditions used by Liu and Chou [13].	43
Table 3.5 VT cooling conditions used by Liu and Chou [13].	43
Table 3.6 Experimental conditions used by Liu and Hu [14].	45
Table 3.7 Turning experimental conditions used by Su et al. [15].	47
Table 3.8 Milling experimental conditions used by Su et al. [15].	47
Table 3.9 Experimental conditions used by Choi et al. [16].	51
Table 3.10 Cooling conditions used by Choi et al. [16].	51
Table 3.11 Report applications of VT cooling.	56
Table 4.1 Summery of workpiece materials machined by RUM.	62
Table 4.2 Mechanical properties of silicon (SolidWorks software database).	65
Table 4.3 High and low levels of input variables.	66
Table 4.4 Test matrix and experimental results.	69
Table 4.5 Effects on edge chipping thickness.	70
Table 4.6 Effects on cutting force.	72
Table 5.1 Experiment results for effects of spindle speed.	93
Table 5.2 Experiment results for effects of feedrate.	93

Table 5.3 Experiment results for effects of ultrasonic power.	94
Table 6.1 Experimental conditions.	119
Table 6.2 Properties of stainless steel (15-5).	120
Table 6.3 Tool weight data before and after test.	123
Table 7.1 Reported materials machined by RUM.	134
Table 7.2 Low and high levels of process variables.	137
Table 7.3 Test matrix and results.	137
Table 8.1 Low and high levels of process variables.	154
Table 8.2 Experiment matrix and results.	155
Table 9.1 Experiment conditions.	170
Table 9.2 Stainless steel properties.	171
Table 10.1 Specifications of the tools.	193
Table 11.1 Values of input variables.	211
Table 12.1 Properties of workpiece material.	228
Table 12.2 Tool parameters.	231
Table 12.3 Machining conditions.	231
Table 13.1 Properties of workpiece material.	254
Table 13.2 Input variables and their values.	256
Table 13.3 Effects of ultrasonic power on burning ratio using cold air.	267
Table 13.4 Effects of tool rotation speed on burning ratio using cold air.	267
Table 13.5 Effects of feedrate on burning ratio using cold air.	267
Table 14.1 Workpiece material properties.	282
Table 14.2 Input variables and their values.	284

Table 15.1 Workpiece material properties.....	299
Table 15.2 Specifications of carbon fiber structures of different CFRP types.	299
Table 15.3 Input variables and their values.	303
Table 16.1 Workpiece material properties.....	329
Table 16.2 Input variables and their values.	331
Table 17.1 CFRP workpiece and its component properties.....	370
Table 17.2 Identifications of cutting tools in experiments.	372
Table 17.3 Experimental conditions for obtaining K_V	374
Table 17.4 Experimental conditions for model verification.	386
Table 18.1 Material properties of CFRP and its components.....	399
Table 18.2 Material properties of titanium alloy (Ti-6Al-4V).	399
Table 18.3 Experimental conditions.	403
Table 18.4 Summary of reported investigations.	408
Table 19.1 Material properties of CFRP and its components.....	428
Table 19.2 Material properties of titanium alloy (Ti-6Al-4V).	428
Table 19.3 Input variables and their values.	431

Acknowledgements

First, I would like to thank my major advisor Dr. ZJ Pei for accepting me as his student. This was a very important turning point of my life and allowed me to enter a new and high stage. In addition, he continuously supported my research and my personal life. His strict attitude toward research and guidance inspired me all the time in the research and made me learn and improve a lot. I had huge changes during these years.

I would like to thank Dr. Shuting Lei, Dr. Jack Xin, and Dr. Haiyan Wang to serve as my supervisory committee members. I also wish to thank Dr. Kenneth J. Klabunde to serve as the outside chairperson of my final examination.

I would like to give my gratitude to U.S. National Science Foundation for the financial support. I would like to extend my thanks to Mr. Clyde Treadwell from Sonic-Mill Inc., Albuquerque, New Mexico, and Mr. Bruno Renzi from N.B.R. Diamond Tool Corporation, Lagrangeville, New York, for providing valuable advice, technical support, and tools for the research.

I really appreciate the encouragement and help from Dr. Bradley A. Kramer and all the faculty and staff members in the Department of Industrial and Manufacturing Systems Engineering.

Special thanks go to Dr. Defu Liu, Dr. Yongjun Tang, Dr. Pengfei Zhang, Dr. Qiangguo Wang, Dr. Qiang Feng, Dr. Na Qin, Mr. Meng Zhang, Mr. Yufan Wang, Ms. Qi Zhang, Ms. Xiaoxu Song for their generous help in my research or my life.

Dedication

TO MY WIFE

XIN SUN

TO MY SON

XINCHEN (AARON) CONG

TO MY PARENTS

ZHI CONG AND SHAOQING JIN

TO MY GRANDPARENTS

PEILUN CONG AND HEFANG QI

Chapter 1 - Introduction

1.1 Introduction of high-performance materials and their drilling methods

1.1.1 Silicon

Silicon, a hard and brittle material, is widely used in semiconductor industry, such as silicon wafers and silicon solar panels [Moss and Ledwith, 1987; Quirk and J. Serda 2001; Moss and Ledwith, 1987; Williams, 1996; Baldwin et al., 2010; Castellano, 2010]. Machining methods for silicon wafers or silicon solar panels include slicing, lapping, grinding, polishing, etc. [Quirk and Serda, 2001; Bawa et al., 1995; Fukami et al., 1997]. In order to increase the efficiency of silicon-based solar panels, metal wrap through (MWT) solar panels were developed. In this kind of silicon solar panels, electrical contacts of the front side need to be connected to the back side of the panel. This requires drilling holes of different sizes on these silicon panels [Mayerhofer et al., 2006; Stonerg et al., 2009].

Several methods have been reported to drill silicon workpieces. Laser drilling was reported to drill holes (in silicon) with diameters ranging from 30 to 100 μm . Larger holes were drilled by a relative movement between laser beam and workpiece. A shortcoming of laser drilling is the existence of heat affected zone (HAZ) around the drilled hole [Yokotani et al., 2005; Stolberg et al., 2009; Miyamoto et al., 2001; Mayerhofer et al., 2006; Geng et al., 2007; Asada et al., 2000]. Electrical discharge machining (EDM) was used to drill holes whose diameters were less than 1 mm [Reynaert et al., 1997]. Microwave drilling was reported to drill holes (in silicon) with diameters ranging from 1 to 10 mm [Jerby et al., 2002]. The diameters of holes drilled on silicon using ultrasonic vibration-assisted (UV-A) drilling (with the ultrasonic

workpiece holder) were less than 1 mm [Tsui et al. 2008]. These reported methods (except for UV-A drilling) belong to thermal non-traditional machining methods. The common drawbacks of these methods include heat affected zone and silicon oxidation. It is desirable to find drilling methods that can produce larger holes and do not cause any HAZ or silicon oxidation.

1.1.2 Aerospace stainless steels

Stainless Steels are widely utilized in aerospace, chemical, and medical industries [Liu et al, 2006; Dolinsek, 2003; Urmann, 2008]. 15-5 stainless steel is one of the important aerospace stainless steels. Characteristics of stainless steels, such as high ductility, poor thermal conductivity, and severe strain hardening, can lead to high temperature and cutting force during machining. As a result, efficiency and tool life are low when drilling stainless steels [Zhong et al., 2004; Jing et al., 2005; Liu et al, 2006; Dolinsek, 2003; Kosmol et al., 1999; Li et al. 2006a; Liu et al. 2006; Chen et al. 2006; Chen et al. 2007; Deng et al. 1993].

Twist drilling and its derivative methods are widely used to produce holes on stainless steel. These twist drilling methods often have the following problems: large thrust force, high drilling temperature, short tool life, and difficult chip exiting. To improve twist drilling, a coating of TiN, TiAlN, or TiCN has been used and the point and helix angles optimized [Jing et al. 2005], however, these improved methods still cannot meet requirements of high-efficient drilling for stainless steels [Li et al., 2006b; Dolinsek, et al., 2003; Sun, 1999; Kosmol, 1999].

Composite/Metal stacks (for example, CFRP/Steel) are used increasingly in newer generations of aircraft. The use of these stacks has resulted in greater challenges to twist drilling. Twist drills wear quickly when drilling composite materials and they often produce burrs at both entrances and exits of the holes in stainless steel. Frequently, subsequent processes are needed to remove these burrs.

1.1.3 Titanium alloys

The primary applications of titanium and its alloys (Ti) are in the aerospace industry for aircraft frames (such as wings and body), gas turbine engines (such as blades, discs, and rotors), and others (such as pipes, clips, and brackets) [Boyer, 1996; Peacock, 1988]. For example, on Boeing 787, the use of Ti has been expanded to roughly 14% of the total airframe [Hale, 2006]. Ti is also used in industries such as military [Montgomery and Wells, 2001; Lerner et al., 2004], automotive [Yamashita et al., 2002; Wilhelm 1993], chemical [Farthing, 1979; Orr, 1982], medical [Fores, 2002; Abdullin et al., 1988], sporting goods [Yang and Liu, 1999], and marine equipment [Eaugwu and Wang, 1997].

Superior properties of Ti include high strength-to-weight ratio, creep and fatigue strength, fracture toughness, heat and corrosion resistance, and shock resistance [Froes et al., 1998; Kumar, 1991; Yang and Liu 1999; Aust and Niemann, 1999]. Due to these superior properties, Ti has been classified as a difficult-to-machine material.

Many Ti components require drilling operations. However, drilling of Ti usually has high cost and low efficiency with current drilling methods. Increasing the use of Ti/composite stacks in the aerospace industry presents even greater challenges.

1.1.4 Carbon fiber reinforced plastic (CFRP) composites

Carbon fiber reinforced plastic (CFRP) composites are composed of strong carbon fibers and plastic matrix. The fibers are used to support the load. The matrix serves to distribute, hold, and protect the fibers and also to transmit the load to the fibers [Gay et al., 2003; Tong et al., 2002; Chung 2010].

CFRP composites are increasingly used as the primary structural materials in the aerospace industry [Mangalgiri, 1999]. For example, in a newer generation of aircraft (such as

Boeing 787), 50% of the weight was made of composites (about 35 tons). This change could lead to 20% high fuel efficiency [Garrick, 2007; Boeing Co. web; Hale, 2006]. CFRP composites are also used in other types of structures including automobile, ship, bridge, athletic equipment, leisure goods, engine blades, power transmission shafts, machine spindles, robot arms, pressure vessels, and chemical containers [Park et al., 1995; Ruegg and Habermeier, 1981; Gay et al., 2003; Guu et al., 2001; Arul et al., 2006; Sadat, 1995].

Superior properties of CFRP include low density (lower than aluminum); high strength (as strong as high-strength steels); high stiffness (stiffer than titanium); good toughness; good fatigue, creep, wear, and corrosion resistance; low friction coefficient; good dimensional stability (about zero coefficient of thermal expansion); and high vibration damping ability [Chung DDL 2010; Arul et al. 2006; Sadat et al. 1995; Davim and Reis 2003; Lambert 1987; Guu et al., 2001; Mallick 1997; Schwartz 1992; Morgan 2005; Park et al. 1995; Ruegg and Habermeier 1981]. Due to some of these superior properties, CFRPs are very difficult to machine.

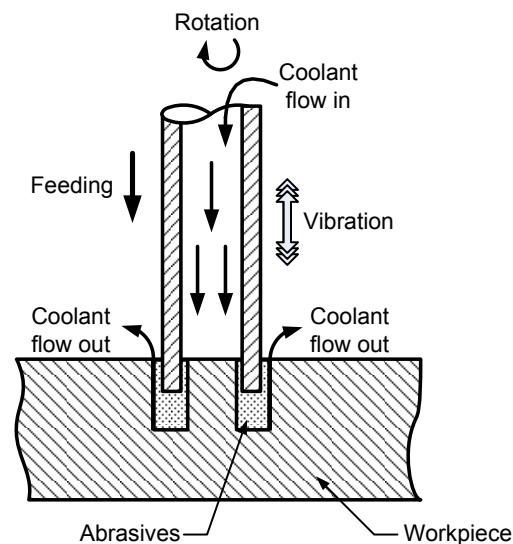
A large number of holes need to be drilled on CFRP for many applications (especially in aircraft assembling) [Boeing Co. Web; Enemuoh et al., 2001; Tsao and Hocheng, 2005; Sprow, 1987; Chung, 2010; Gay et al., 2003]. Therefore, it is important to develop cost-effective drilling processes. Twist drilling and its derivative methods are widely used to produce holes on composites [Ramulu et al. 2001; Tsao and Hocheng, 2005a; Tsao and Hocheng, 2004; Campos Rubio et al., 2008; Davim and Reis, 2003b]. These methods have such shortcomings as short tool life and poor hole quality [Wong et al. 1982]. Since holes are often drilled in finished products, part rejections due to poor hole quality are very costly [Tsao and Hocheng, 2005b; Abrate and Walton, 1992].

1.2 Introduction of rotary ultrasonic machining

Rotary ultrasonic machining (RUM) is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining (USM). Experiments with calcium aluminum silicate and magnesia stabilized zirconia have shown that the MRR obtained from RUM is six to ten times higher than that from a conventional grinding process under similar conditions [Prabhakar, 1992]. In comparison with USM, RUM is about ten times faster; it is easier to drill deep holes with rotary ultrasonic machining than with USM; and the hole accuracy is improved [Cleave, 1976; Graff, 1975]. Other advantages of this process include superior surface finish and low tool pressure [Cleave, 1976; Petrukha et al., 1970].

Figure 1.1 illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During machining, the rotating tool vibrates axially at an ultrasonic frequency (typically 20 kHz) and feeds along its axial direction towards the workpiece. Coolant is pumped through the core of the cutting tool, washing away the swarf and preventing the cutting zone from overheating.

Figure 1.1 Illustration of rotary ultrasonic machining.



1.3 Structures and objectives of this research

This Ph.D. dissertation consists of twenty chapters. Firstly, an introduction of research is given in Chapter 1. Secondly, Chapters 2 and 3 present two literature reviews on silicon drilling and dry drilling, respectively. Then, design of experiment and finite element analysis on edge chipping in RUM of silicon are presented in Chapter 4. Chapters 5 ~ 9 talk about investigations on RUM of aerospace stainless steels. Chapters 10 and 11 discuss development processes of an ultrasonic vibration amplitude measurement method and a cutting temperature measurement method using titanium alloys as workpiece. Chapters 12 ~ 17 discuss experimental and theoretical investigations on RUM of CFRP composites. Two experimental studies of CFRP/Ti stacks are presented in Chapters 18 and 19. Finally, conclusions and contributions on RUM drilling are given in Chapter 20.

The objectives of the research is to provide new knowledge on drilling of high-performance materials (silicon, stainless steels, titanium alloys, and CFRP composites) using rotary ultrasonic machining. Specific research tasks are as follows:

- (1) On RUM of silicon, studying interaction effects of input variables on cutting force and edge chipping and developing a finite element analysis (FEA) model on the relationship between cutting force and edge chipping.
- (2) On RUM of aerospace stainless steel, comparing superabrasive tools, investigating effects of machining variables on cutting force, torque, and surface roughness, conducting design of experiment, and testing hypothesis about surface roughness.
- (3) On RUM of titanium, developing a vibration amplitude measurement method and a cutting temperature measurement method.

- (4) On RUM of CFRP, conducting feasibility study to compare twist drilling and RUM, testing drilling with cold air (comparing with cutting fluid and testing feasible cutting regions), studying power consumption and cutting temperature, and developing a predictive model for cutting force.
- (5) On RUM of CFRP/Ti Stacks, conducting feasibility study to compare RUM with other reported drilling methods and testing drilling with variable feedrate (comparing with fixed feedrate).

References

Abdullin I., Bagautinov A., Ibragimov G., 1988, Improving surface finish for titanium alloy medical instruments, *Biomedical Engineering*, 22(2), pp. 48-50.

Abrate S. and Walton D.A., 1992, Machining of composite materials. Part I: Traditional method, *Composites Manufacturing*, 3(2), pp. 75-83.

Arul S., Vijayaraghavan L., Malhotra S.K., and Krishnamurthy R., 2006, The effect of vibratory drilling on hole quality in polymeric composites, *International Journal of Machine Tools and Manufacture*, 46(3-4), pp. 252-259.

Asada S., Sano T., and Miyamoto I., 2000, High efficient microdrilling of silicon wafer using excimer laser, *Proceeding of SPIE - The International Society for Optical Engineering*, June 14-16, Omiya, Japan.

Aust E. and Niemann H., 1999. Machining of gamma Ti-Al, *Advanced Engineering Materials*, 1(1), pp. 53-57.

Bawa M.S., Petro E.F., and Grimes H.M., 1995, Fracture strength of large diameter silicon wafers, *Semiconductor International*, Vol. 18, pp. 115-118.

Boeing Co. website, 787 Dreamliner Program Fact Sheet, <http://www.boeing.com/commercial/787family/programfacts.html>.

Boyer R., 1996, Overview on the use of titanium in the aerospace industry, *Materials Science and Engineering A: Structure Materials, Properties, Microstructure, and Processing*, 213 (2), pp. 103-114.

Campos Rubio J.C., Abrão A.M., Eustáquio Faria P., Correia A.E., and Davim J.P., 2008, Delamination in high speed drilling of carbon fiber reinforced plastic (CFRP), *Journal of Composite Materials*, 42(15), pp. 1523-1532.

Castellano R., 2010, *Solar Panel Processing*, Old City Publishing Inc, Philadelphia, PA, USA.

Chen M., Liu G., and Zhang X.H., 2007, Optimization studies on hole-making tools for high-performance cutting austenitic stainless steel, *Machining Science and Technology*, 11(2), pp. 183-200.

Chen M., Liu G., Jing L.L., Hu Z.G., Zhu X.F., Li Z.W., and Xu H., 2006, The development of special drills for high-efficient drilling austenitic stainless steel part II: coating selection and experiment research, *Key Engineering Materials*, Vol. 315-316, pp. 200-204.

Chung D.D.L., 2010, *Composite Materials Science and Applications*, 2nd edition, Springer London Ltd, London, UK.

Cleave D., 1976, Ultrasonic gets bigger jobs in machining and welding, *Iron Age*, September, pp. 69-72.

Davim J.P. and Reis P., 2003, Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, *Materials and Design*, 24(5), pp. 315-324.

Davim J.P. and Reis P., 2003b, Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments, *Composite Structures*, 59(4), pp. 481-487.

Deng G.P., Li S.Z., Wu S.Q., and Yang X.G., 1993, Ultrasonic vibration drilling of small-diameter deep holes of difficult-to-machine stainless steel: theoretical analysis and comparative experimental research, *Proceedings of the 1993 ASME Winter Annual Meeting*, November 28 - December 3, New Orleans, LA, USA, pp.835-839.

Dolinsek S., 2003, Work-hardening in the drilling of austenitic stainless steels, *Journal of Materials Processing Technology*, 133(1-2), pp. 63-70.

Dolinsek S., 2003, Work-hardening in the drilling of austenitic stainless steels, *Journal of Materials Processing Technology*, 133(1-2), pp. 63-70.

Enemuoh E.U., El-Gizawy A.S., and Okafor A.C., 2001, An approach for development of damage-free drilling of carbon fiber reinforced thermosets, *International Journal of Machine Tools and Manufacture*, 41(12), pp. 1795-1814.

Ezugwu E.O. and Wang Z.U., 1997, Titanium alloys and their machinability-a review, *Journal of Materials Processing Technology*, 68(3), pp. 262-274.

Farthing T., 1979, Application of titanium in the chemical industry, *Chemical Age of India*, 30(2), pp. 151-166.

Froes F., 2002, Titanium sport and medical application focus, *Materials Technology*, 17(1), pp. 4-7.

Froes F., Allen P., and Niinomi M., 1998, Non-aerospace application of titanium: an overview, *Proceedings of Minerals, Metals and Materials Meeting*, Minerals, Metals and Materials Society, February 16-18, Warrendale, PA, USA, pp. 89-97.

Fukami T., Masumura H., Suzuki K., and Kudo H., 1997, Method of Manufacturing Semiconductor Mirror Wafers, European Patent Application EP0782179A2.

Garrick R., 2007, Drilling advanced aircraft structures with PCD (Poly-Crystalline Diamond) drills, AeroTech Congress & Exhibition, September, Los Angeles, CA, USA.

Gay D., Hoa S.V., and Tsai S.W., 2003, Composite Materials Design and Applications, 4th edition, CRC press, Boca Raton, FL, USA.

Geng N., Fu X., Li H.X., Ni X.C., and Hu X.T., 2007, Effects of laser parameters in the micromachining of silicon by femtosecond pulse laser, Key Engineering Materials, Vol. 339, pp. 136-140.

Graff K., 1975, Ultrasonic machining, Ultrasonic, May, pp. 103-109.

Guu Y.H., Hocheng H., Tai N.H., and Liu S.Y., 2001, Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, Journal of Materials Science, 36(8), pp. 2037-2043.

Hale J., 2006, Boeing 787 from the ground up, AERO 24 (Quarter 4), pp. 17-23, available at:
http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_1.html.

Jana J. and Satyanarayana A., 1973, Production of fine diameter holes on ultrasonic drilling machining, Journal of the Institution of Engineers (India), Part MC: Mechanical Engineering Division, 54 (1), pp. 36-40.

Jerby E., Dikhtyar, V., Aktushev, O., Groslick, U., 2002, The microwave drill, Science, Vol. 298, pp. 587-589.

Jing L.L., Li Z.Y., Chen M., Sun F.H., Hu Z.G., Zhu X.F., Li Z.W., and Xu H., 2005, Experimental study on the cutting deformation in drilling austenitic stainless steel, Journal of Shanghai Jiaotong University, 39(11), pp. 1746-1750. (in Chinese)

Kosmol J., Czech M., Klarecki K., and Sliwka J., 1999, Optimisation of drills for the machining of austenitic steel, Journal of Materials Processing Technology, Vol. 89-90, pp. 117-122.

Kosmol J., Czech M., Klarecki K., and Sliwka J., 1999, Optimizations of drills for the machining of austenitic steel, Journal of Materials Processing Technology, 89-90(May), pp. 117-122.

Kumar K.V., 1991, Grinding titanium, Aerospace Engineering, 11(9), pp. 17-19.

Lambert B.K., 1987, Cutting and drilling of composite materials, Carbide Tool Journal, Vol. 19, pp. 31-34.

Legge P., 1966, Machining without abrasive slurry, Ultrasonics, Vol. 2, pp. 157-162.

Lerner I., 2004, Titanium market recovering on commercial military aircraft, Chemical Market Reporter, 266(18), pp. 17.

Li X.K., Chen Z.B., Chen M., Hu Z.G., Zhu X.F., and Li Z.W., 2006a, Research on wear mechanism of coated HSS drills during machining stainless steel, China Mechanical Engineering, 17(4), pp. 354-361. (in Chinese)

Li X.K., Chen Z.B., Chen M., Hu Z.G., Zhu X.F., and Li Z.W., 2006b, Research on Wear Mechanism of Coated HSS Drills During Machining Stainless Steel, China Mechanical Engineering, 17(4), pp. 354-361. (in Chinese)

Lindroos V., Tilli M., Lehto A., and Motooka T., (Editors), 2010, Handbook of Silicon Based MEMS Materials and Technologies, Elsevier, Oxford, UK.

Liu G., Chen M., Jing L.L., Hu Z.G., Zhu X.F., Li Z.W., and Xu H. (2006) ‘The development of special drills for high-efficient drilling austenitic stainless steel - part I: drill comparison and experiment research’, Key Engineering Materials, Vol.315-316, pp. 195-199.

Mallick P.K., 1997, Composite Engineering Handbook, Marcel Dekker Inc., New York, NY, USA.

Mangalgiri P.D., 1999, Composite materials for aerospace applications, Bulletin of Materials Science, 22(3), pp. 657-664.

Mayerhofer, R., Müllers, L., Becker A., 2006, “Laser micro-processing in solar cell production”, Proceeding of the IEEE 4th World Conference on Photovoltaic Energy Conversion, WCPEC-4, May 7-12, Waikoloa, HI, USA, 1, pp. 1115-1118.

Miyamoto I., Asada S., Sano T., and Ohmura E., 2001, High speed drilling of thin silicon wafer by UV laser, Proceeding of International Congress on Applications of Lasers and Electro-Optics, October 15-18, Jacksonville, FL, USA, pp. 1612-1619.

Montgomery J. and Wells M., 2001, Titanium armor applications in combat vehicles, Journal of Machining, 53(4), pp. 29-32.

Morgan P., 2005, Carbon Fibers and their composites, CRC Press, Taylor & Francis Group, Boca Raton, FL, USA.

Moss S.J. and Ledwith A., 1987, Chemistry of the Semiconductor Industry, Blackie & Son Limited, London, UK.

Orr N., 1982, Industrial application of titanium in the metallurgical industries and chemical industries, Proceedings of Technical Sessions at the 111th American Institute of Mining, Metallurgical and Petroleum Engineers, February 14-18, Dallas, TX, USA,

Park K.Y., Choi J.H., and Lee D.G., 1995, Delamination-free and high efficiency drilling of carbon fiber reinforced plastics, *Journal of Composite Materials*, 29(15), pp. 1988-2002.

Peacock D., 1988, Aerospace applications for titanium, *Sheet Metal Industries*, 65(8), pp. 406-408.

Petrukha P., 1970, Ultrasonic diamond drilling of deep holes in brittle materials, *Russian Engineering Journal* 50(10), pp. 70-74.

Prabhakar D., 1992, Machining advanced ceramic materials using rotary ultrasonic machining process, M.S. Thesis, University of Illinois at Urbana-Champaign, USA.

Quirk M. and Serda J., 2001, *Semiconductor Manufacturing Technology*, (Chapter 4 pp. 67-90), Pearson Education International, Columbus, OH, USA.

Ramulu M., Branson T., and Kim D., 2001, A study on the drilling of composite and titanium stacks, *Composite Structure*, 54(1), pp. 67-77.

Reynaerts D., Heeren P.H., and Brussel H.V., 1997, Microstructuring of silicon by electro-discharge machining (EDM)- part I: theory, *Sensors and Actuators A: Physical*, 60(1-3), pp. 212-218.

Ruegg C.H., and Habermeier J., 1981, Composite propeller shafts: design and optimization, *Automotive Engineer*, 6(3), pp. 13-15.

Sadat A.B., 1995, Delamination and other types of damage of graphite/epoxy composite caused by machining, *Applied Mechanics Division and the Materials Division: Machining of Advanced Materials*, June 28-30, Los Angeles, CA, pp. 41-52.

Schwartz M., 1992, *Handbook of Structural Ceramics*, McGraw-Hill Inc., New York, NY, USA.

Sprow E.E., 1987, Cutting composite: Three choices for any budget, Tooling & Production, 43(12), pp. 46-50.

Stolberg K.P., Kremser B., Friedel S., and Atsuta, Y., 2009, Systematic optimisation of process parameters in laser drilling of 200 μm photovoltaic silicon wafers using new kind of nanosecond IR lasers, Journal of Laser Micro/Nanoengineering, 4(3), pp. 231-233.

Sun Y., 1999, Kinematics-Driven Modeling and Grinding Path Generation for Drill Geometry, Ph.D. Dissertation, The University of Michigan, USA.

Tong L., Mouritz A.P., and Bannister M.K., 2002, 3D Fibre Reinforced Polymer Composites, Elsevier Science Ltd, Oxford, UK.

Tsao C.C. and Hocheng H., 2004, Taguchi analysis of delamination associated with various drill bits in drilling of composite material, International Journal of Machine Tools and Manufacture, 44(10), pp. 1085-1090.

Tsao C.C. and Hocheng H., 2005a, Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials, International Journal of Machine Tools and Manufacture, 45(2), pp. 125-130.

Tsao C.C. and Hocheng H., 2005b, Computerized tomography and C-Scan for measuring delamination in the drilling of composite materials using various drills, International Journal of Machine Tools and Manufacture, 45(11), pp. 1282-1287.

Tsui C.Y., Lu M.C., Wu C.C., and Huang, C.F., 2008, Drilling of microholes on silicon wafer with ultrasonic workpiece holder, Proceeding of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, August 3-6, Brooklyn, NY, USA.

Urmann D.H., 2008, Useful Applications of Stainless Steel, available at: <http://www.articlesbase.com/home-improvement-articles/useful-applications-of-stainless-steel-587256.html>, [accessed 1/1/2009].

Wilhelm M., 1993, Material used in automobile manufacturing - current state and perspectives, *Journal de Physique IV*, 3(11), pp. 31-40.

Williams M.E., Baldwin D.G., and Manz P.C., 1996, *Semiconductor Industrial Hygiene Handbook: Monitoring, Ventilation, Equipment and Ergonomics*, Noyes Publication, Park Ridge, NJ, USA.

Wong T.L., Wu S.M., and Croy, G.M., 1982, An analysis of delamination in drilling composite materials, *Proceedings 14th SAMPLE Technology Conference*, Atlanta, GA, USA.

Yamashita Y., Tkayama I., Fujii H., and Yamazaki, T., 2002, Applications and features of titanium for automotive industry, *Nippon Steel Technical Report*, (85), pp. 11-14.

Yang X. and Liu C.R., 1999, Machining titanium and its alloys, *Machining Science and Technology*, 3(1), pp. 107-139.

Yokotani A., Mukumoto T., Kanamitsu Y., Fukumoto H., and Kurosawa K., 2005, Time-resolving image analysis of drilling of thin silicon substrates with femtosecond laser ablation, *Japanese Journal of Applied Physics, Part 1: Regular Papers, Short Notes & Review Papers*, 44(11), pp. 7998-8003.

Zhong J.W., Ma Y.P., Sun F.H., and Chen M., 2004, Research on high-speed drilling performances of austenitic stainless steels, *Journal of Shanghai Jiaotong University*, 38(2), pp. 83-88. (in Chinese)

Chapter 2 - Literature Review – Silicon Drilling

Paper title:

Drilling of silicon based solar panels: a review

Published in:

Proceedings of the ASME 2010 International Manufacturing Science & Engineering Conference (MSEC-2010), October 12-15, 2010, Erie, PA, USA

Authors' names:

Cong, W.L., Feng, Q., and Pei, Z.J.

Authors' affiliations:

Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

Abstract

Solar panels have been developed to convert the solar energy to electricity. Since most solar panels are silicon based, they inherit the mechanical properties of silicon, such as brittleness and hardness. These properties might lead to cracking in workpieces and low tool lives in traditional machining processes. In solar panel manufacturing, to increase the efficiency of solar cells, electrical contacts on the front side of the panel need to be connected to those on the back side. Therefore, holes of different sizes are required to drill in silicon solar panels for certain designs. This paper reviews the literature on different drilling processes for silicon solar panels and summarizes merits, shortcomings, and special characteristics of each method.

Keywords: Drilling, Silicon, Solar panel, Laser drilling, Microwave drilling, Electro-discharge machining, Ultrasonic vibration assisted drilling, Rotary ultrasonic machining.

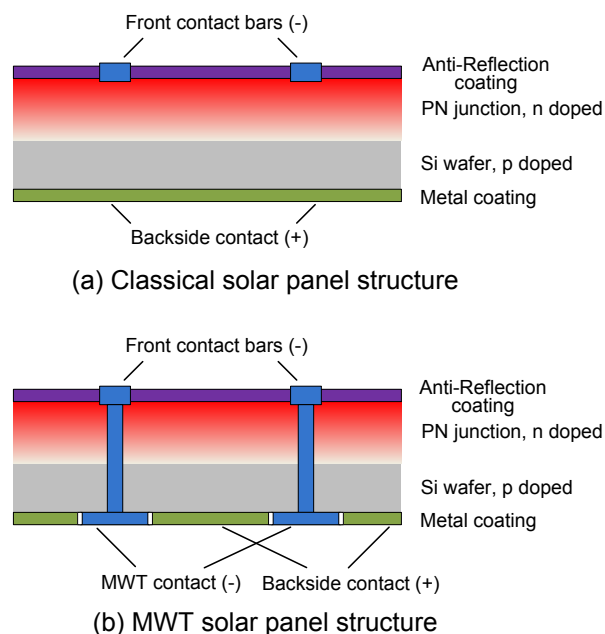
2.1 Introduction

Global economics need continuous support of energy. The world total energy supply has more than doubled from 1971 to 2007 [1]. Fossil fuels take more than 80% of the total energy supply in 2009 [1]. However, fossil fuels are non-renewable and cannot satisfy human's need for a long time. In addition, burning of fossil fuels is criticized for emitting greenhouse gasses, toxic substances and particulate materials to the water, the land and the atmosphere [2,3]. Therefore, it is vital to have renewable energy sources (such as solar, hydroelectric, geothermal, biomass, and wind) [4].

Solar panels are the main cost of solar energy systems. At present, a regular solar panel is not efficient, transferring only about one sixth of the sunlight entering it into electricity [5]. Among the challenges to solar panel manufacturing is improving the efficiency while reducing costs [5]. In solar panel manufacturing, to increase the efficiency of solar cells, it is required to

arrange contacts within short distances. For a typical solar cell (as shown in Figure 2.1a), about 10% of the entire area is taken up by the front contact pattern. In order to reduce shadowing of the front contact pattern, a large area of back contacts and front side bars are used. “Wrapped through” micro-vias to the backside (point contacts), as illustrated in Figure 2.1b, is designed [6,10,11]. Metal wrap through (MWT) solar panels are capable of achieving solar energy conversion efficiencies of over 21% [12]. In MWT panels, electrical contacts on the front side of the panel need to be connected to those on the back side. This requires drilling holes of different sizes on silicon panels [6,13].

Figure 2.1 Illustrations of solar panel structures (after [6-9]).



Research has been conducted on various drilling processes on silicon solar panels or other silicon workpieces. There are no review papers in the literature on drilling of silicon workpieces. Such review papers would be desirable since they can provide comprehensive

information on silicon drilling to decision makers when they choose a drilling process for silicon solar panels.

This paper reviews several drilling methods for silicon solar panels or other silicon workpieces in the literature. These methods include laser drilling, microwave drilling, electro-discharge machining, ultrasonic vibration assisted drilling, and rotary ultrasonic machining. For each method, principles and characteristics, important process parameters, and output variables are described. Finally, reported experiments are summarized.

2.2 Laser drilling

2.2.1 Principle of laser drilling

In laser drilling, intense laser beams focus on the workpiece and generate high temperature in a very short time and drill the workpiece by melting and vaporizing the workpiece material [14]. Figure 2.2 schematically illustrates laser drilling. There are several types of laser drilling methods (as illustrated in Figure 2.3), such as single pulse, percussion, trepanning, and helical [16]. The single pulse and percussion methods have stationary laser beam (without having relative movement between laser beam and workpiece). The percussion method (laser operates in a repeated manner with short pulses, ranging from 10-12 to 10-13 s, separated by longer time periods) produces better holes than the single pulse method. Holes with diameters in the range of 30-100 μm are produced by the percussion method. Larger holes are drilled using a relative movement between laser beam and workpiece (trepanning cutting) [13,17]. The helical method (In this case, the specimens are moved up and down to achieve a positive or negative focusing position) is usually used for drilling thicker workpieces.

Figure 2.2 Schematic illustration of laser drilling (after [14,15]).

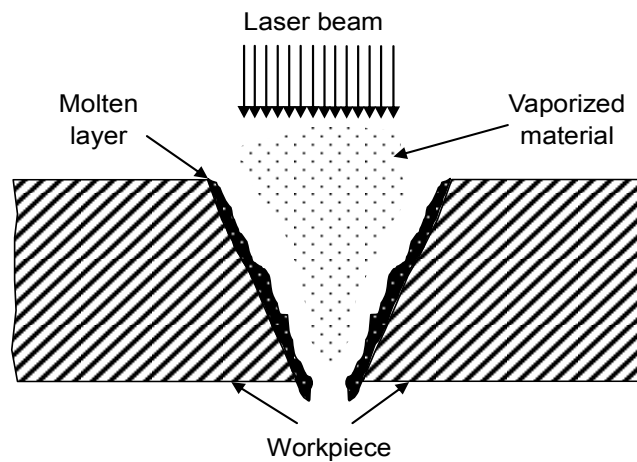
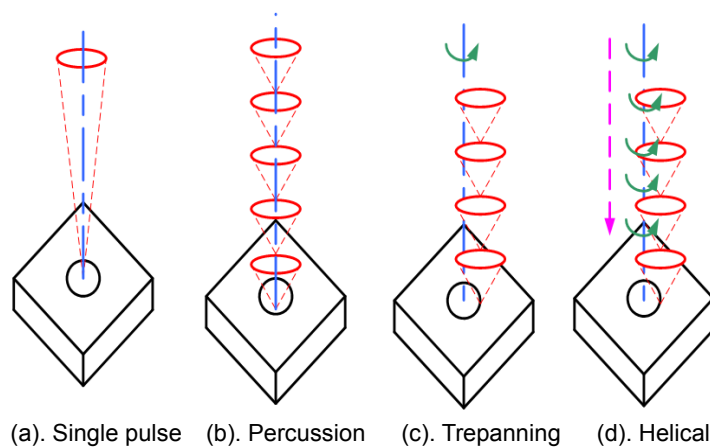


Figure 2.3 Several methods of laser drilling (after [15,16]).



2.2.2 Characteristics of laser drilling

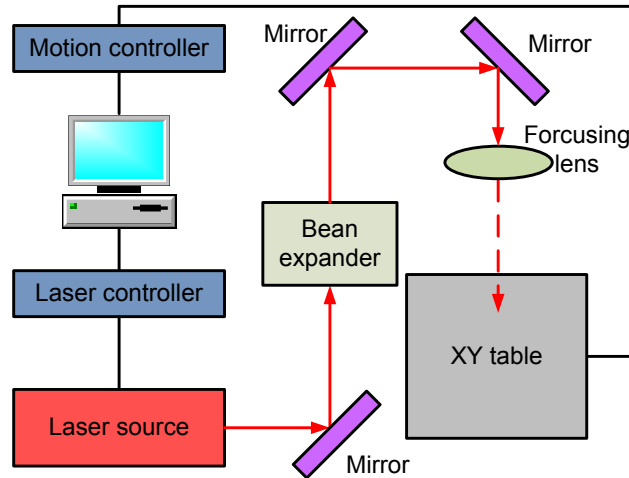
The advantages of laser drilling include: (1) Non-contact processing; (2) No tool wear; (3) High speed and high accuracy; and (4) Larger holes can be drilled using the trepanning method [15].

Laser drilling also has some disadvantages. The main disadvantages are heat-affected zone, high energy required, and harmful laser radiation. In addition, silicon workpieces may be oxidized under high temperature caused by laser drilling.

2.2.3 Laser drilling system set-up

Figure 2.4 shows a typical laser drilling system. This system mainly consisted of a laser source, a beam expander, delivery optics (mirrors), focusing lens, movable XY table with workpiece holder, motion controller, and laser controller.

Figure 2.4 Schematic diagram of a laser drilling system (after [15]).



2.2.4 Experimental investigations

Important input variables include laser power, laser pulse repetition rate, laser pulse duration, laser pulse energy, laser fluence, laser beam diameter, and machining time. The hole diameter and drilling rate are the important output parameters. Many papers reported experimental investigations on laser drilling of silicon workpieces. They are summarized in Table 2.1.

Table 2.1 Summary of experimental investigations on laser drilling.

Reference	Laser type	Input variable	Outputs variable	Effect
[15]	Nd: YAG	Laser power	Hole diameter	Positive*
		Laser pulse repetition rate	Hole diameter	Negative**
		Laser machining time	Hole diameter	Positive
[6]	IR pulsed	Laser pulse energy	Hole diameter	Positive
		Laser pulse duration	Drilling rate	---
[18]	Nd: YAG	Laser pulse energy	Hole diameter	Positive
[19]	Femtosecond	Number of pulses	Hole diameter	Positive
		Laser power	Hole diameter	Positive
[20]	Femtosecond	Laser fluence	Hole diameter	Positive
[21]	Femtosecond	Laser pulse energy	Hole diameter	Positive
		Laser machining time	Hole diameter	Positive
[22]	Ti: sapphire	Laser pulse duration	Hole diameter	Positive
[14]	UV	Laser beam diameter	Drilling rate	Negative
		Laser fluence	Drilling rate	Positive
[23]	YAG	Laser beam diameter	Drilling rate	Negative
		Laser fluence	Drilling rate	Positive
[17]	KrF excimer	Laser fluence	Drilling rate	Positive
		Laser machining time	Drilling rate	Positive
[24]	Nd: YLF	Laser power	Drilling rate	Positive
[25]	Femtosecond	Laser fluence	Drilling rate	Positive

* Positive effect means that the output variable increases when the input variable increases.

** Negative effect means that the output variable decreases when the input variable increases.

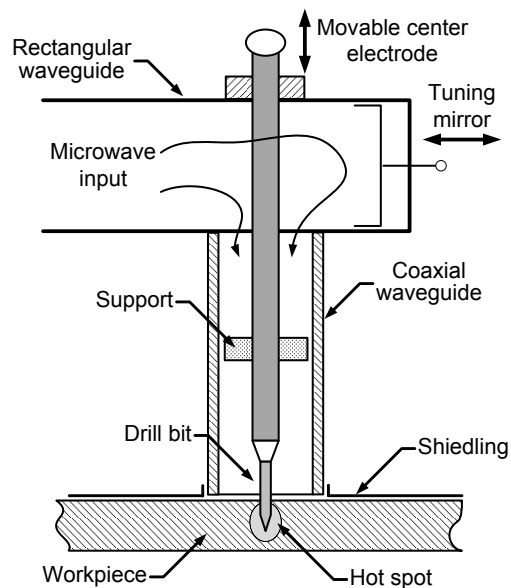
2.3 Microwave drilling

2.3.1 Principle of microwave drilling

The concentration of microwave energy on a small hot spot (much smaller than the microwave wavelength) is the key principle of microwave drilling [26]. The near-field microwave radiator, as illustrated in Figure 2.5, is constructed as a coaxial waveguide ended with an extendable monopole antenna that functions also as the drill bit. Initially, the microwave-energy deposition rate is the highest at the material near the antenna. The subsurface tends to have a slightly higher temperature than the spontaneously cooled surface. Hence, the hottest zone becomes localized underneath the surface. Because hotter material usually absorbs microwaves

better, the energy absorption in the subsurface is further increased. A hot spot is created, and the material becomes soft or molten. The coaxial center electrode is then inserted into this molten hot spot and shapes its boundaries. Finally, the electrode is removed from the hole, while the material cools down in its new shape.

Figure 2.5 Illustration of microwave drilling (after [26]).



2.3.2 Characteristics of microwave drilling

Microwave drilling is capable of drilling a variety of nonconductive materials. Unlike mechanical drilling methods, microwave drilling is quiet and clean. It does not contain fast rotating parts, nor does it cause mechanical friction, and its operation is essentially dust-free. On the other hand, the microwave drilling emits hazardous radiation, and requires safety measures, and, therefore, its operating conditions may be limited.

2.3.3 Microwave drilling system set-up

Microwave drilling integrates electromagnetic-radiation, heating, and mechanical effects, and it could be regarded as a hybrid method. The experimental setup consisted of an adjustable microwave power source (2.45-GHz, 1-kW magnetron), a directional coupler, and an impedance-matching tuner, in a cascade with the microwave-drill head. The latter was made as a rectangular-to-coaxial waveguide transition, as shown in Figure 2.5. The coaxial center electrode as a drill bit is free to move toward the workpiece. This electrode was usually made of a tungsten rod and sustained insertions into materials with melting temperatures up to 1500°C. For higher temperatures the tungsten rod was covered with an alumina tube or replaced by a silicon-carbide tip. The coaxial structure was cooled by a pressurized air flow and thus could support a 1-kW power transmission.

The literature does not have any reports of systematic experimental investigations on microwave drilling.

2.4 Electro-discharge machining (EDM)

2.4.1 Principle of electro-discharge machining

As shown in Figure 2.6, electrical discharge machining (EDM) uses a series of rapidly recurring current discharges (sparks) between tool electrode (as illustrated in Figure 2.7) and workpiece to achieve material removal. In EDM, material removal starts when the generator applies a voltage between the workpiece (the silicon wafer) and a tool electrode (a tungsten wire). This voltage is high enough to produce sparks between the two electrodes. Dielectric fluid is pumped through a nozzle to flush away eroded particles [30]. The remaining melting material solidifies again on the surface of the electrodes. Through appropriate setting of machining

parameters, the material removal on the tool electrode can be kept at least an order of magnitude smaller than the material removal on the workpiece electrode. The net result of the spark is a small crater on both workpiece and tool electrode. By applying a large number of sparks, large material volumes can be removed [27,30-32].

Figure 2.6 Schematic illustration of EDM (after [27,28]).

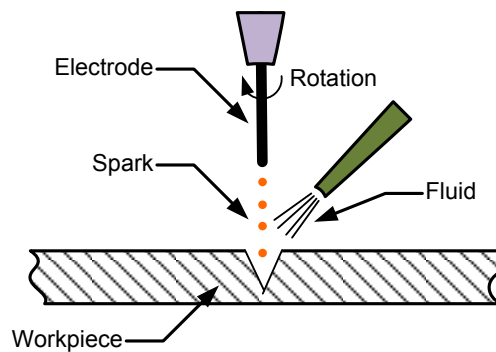
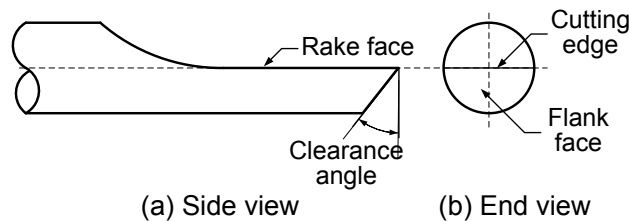


Figure 2.7 Illustration of EDM tool electrode (after [29]).



2.4.2 Characteristics of electro-discharge machining

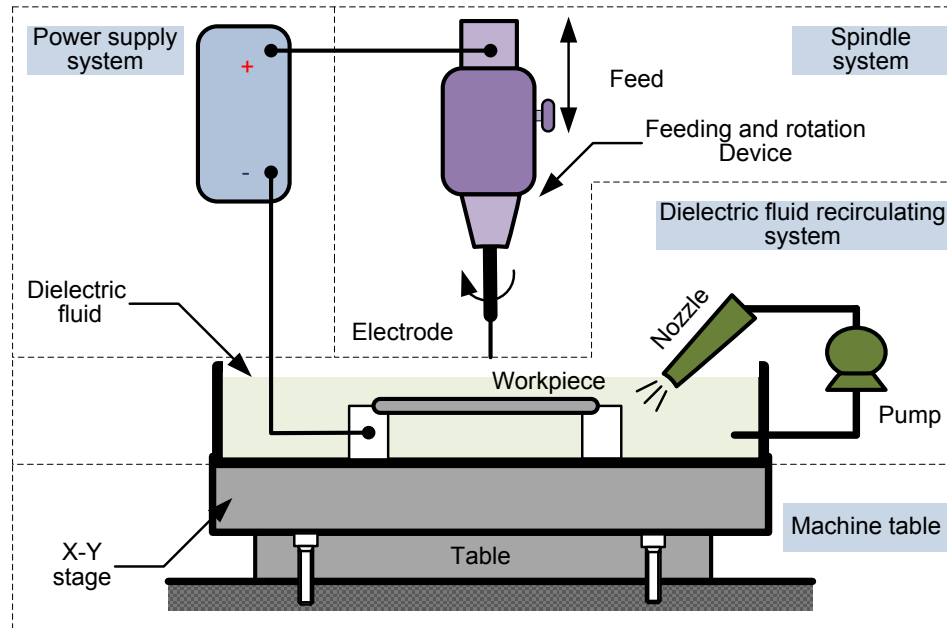
EDM has several advantages for machining silicon compared with other etching-derived techniques. For drilling, it requires a low installation cost and small job overhead (such as designing masks, etc.) [27,30-32].

2.4.3 Electro-discharge machining system set-up

As illustrated in Figure 2.8, a typical EDM system includes spindle system, dielectric fluid recirculating system, power supply system, and machine table. The spindle system consists

of feeding and rotation device and the electrode clamped on the spindle. The power supply system provided current discharges to the electrode. The dielectric fluid recirculating system could pump the fluid to the workpiece [27,30-32].

Figure 2.8 Schematic illustration of a typical EDM system (after [27,28]).



2.4.4 Experimental investigations

Important input variables include electrode current, electrode type, and tool electrode feedrate. Important output variables include material removal rate (MRR), cutting speed, electrode wear rate (EWR), surface roughness, and hole diameter and taper. MRR in EDM represents the erosion rate of the workpiece material. EWR measures the wear rate of the electrode (the tool). The holes produced by EDM are usually tapered due to the unequal durations under spark erosion at different locations of the drilled hole. The hole entrance is exposed to side spark for a longer time period than the hole exit [27,30-32].

Egashira and Mizutani [29] used EDM for micro-drilling of silicon. Their experiments were carried out on a micro-EDM machine. The tool electrode was made of cemented carbide and its geometry is shown in Figure 2.7. The rotation speed was 3000 rpm. They mainly reported effects of tool electrode variables and feedrate on hole diameter. The tool with clearance angle of 0° led to significant larger hole diameters and lower feedrate resulted in smaller hole diameters. They reported that the hole drilled with a tool clearance angle of 0° and feedrate of $0.05 \mu\text{m/s}$ has fractures at the entrance.

2.5 Ultrasonic vibration assisted drilling

2.5.1 Principle of ultrasonic vibration assisted drilling

The cutting tool is made of tungsten carbide. An ultrasonic workpiece holder was designed for generating the vibrations. The workpiece was attached on the top surface of the ultrasonic holder. During drilling, the workpiece vibrates up and down at an ultrasonic frequency and the tool moves along its axial direction towards the workpiece.

2.5.2 Characteristics of ultrasonic vibration assisted drilling

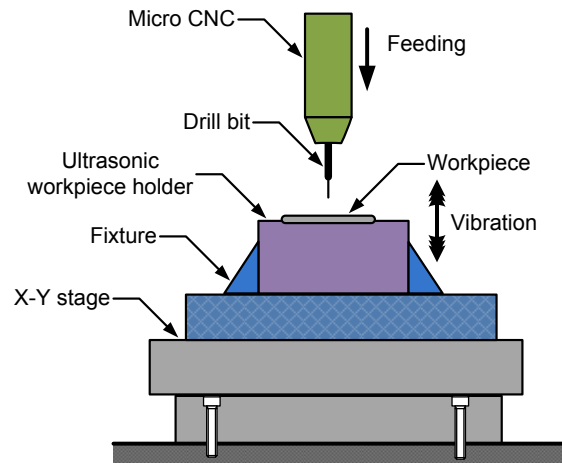
Ultrasonic vibration assisted drilling is a kind of mechanical drilling method. Its advantages include: (1) no heat affected zone; and (2) low power consumption. The main disadvantage is that the workpiece size is limited [33].

2.5.3 Ultrasonic vibration assisted drilling system set-up

Figure 2.9 shows the experimental setup. An ultrasonic workpiece holder installed on the XY table. The drill bit was tungsten carbide with the diameter of $600 \mu\text{m}$. The workpiece was attached onto the top surface of the ultrasonic workpiece holder with double-side adhesive tape

or clamp. The ultrasonic workpiece holder actuated by a piezoelectric transducer (PZT) which was vibrated vertically at a frequency of 20 kHz. In this experiment, the amplitude was set at 1 μm [33].

Figure 2.9 Illustration of ultrasonic vibration assisted drilling (after [33]).



2.5.4 Experimental investigations

Different input parameters (vibrations and feedrates) were used to examine the behavior of output variables, such as drilled hole accuracy, edge chipping on the drilled hole surface, and tool wear. The drilling processes with/without ultrasonic assistance were conducted when other conditions were kept the same. Moreover, three feedrate levels (0.005 mm/min, 0.1 mm/min, and 0.2 mm/min) were used to investigate the combination effects of undeformed chip thickness and ultrasonic vibration on drilling performances [33].

The holes drilled with ultrasonic vibration had smaller chipping area than the holes drilled without ultrasonic vibration when feedrate was 0.01 mm/min and 0.02 mm/min. No significant improvement was observed by the ultrasonic vibration assisted drilling when feedrate was 0.005 mm/min. Smaller hole sizes were observed for the ultrasonic vibration assisted

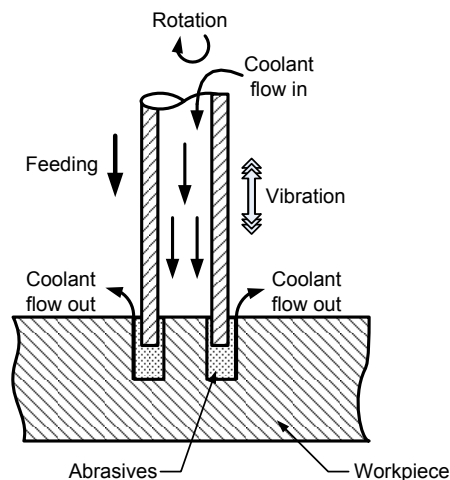
drilling when feedrate was 0.005 mm/min and 0.01 mm/min. Compared to the average tool diameter (0.605 mm), the ultrasonic vibration assisted drilling could provide better size control. Different levels of feedrate and with/without vibration assistance led to different hole diameter. The hole diameters with ultrasonic vibration assistance were larger than those without vibration assistance. Results also provide evidence that the ultrasonic vibration assisted drilling can reduce the tool wear rate in silicon drilling.

2.6 Rotary ultrasonic machining (RUM)

2.6.1 Principle of rotary ultrasonic machining

Rotary Ultrasonic Machining (RUM) is illustrated in Figure 2.10. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrates axially at an ultrasonic frequency and moves along its axial direction towards the workpiece. Coolant pumped through the drill washes away the swarf and prevents the tool from overheating. RUM can drill holes with the diameter ranging from 3.2 mm (1/8 in) to 28.6 mm (1 1/8 in) [34].

Figure 2.10 Illustration of rotary ultrasonic machining (after [34]).



2.6.2 Characteristics of rotary ultrasonic machining

Rotary ultrasonic machining (RUM) is a relatively low-cost, environment-benign process that easily fits in with the infrastructure of the traditional machining environment. Other advantages of this process include high hole accuracy, superior surface finish, low tool pressure, and low tool wear rate.

2.6.3 Rotary ultrasonic machining system set-up

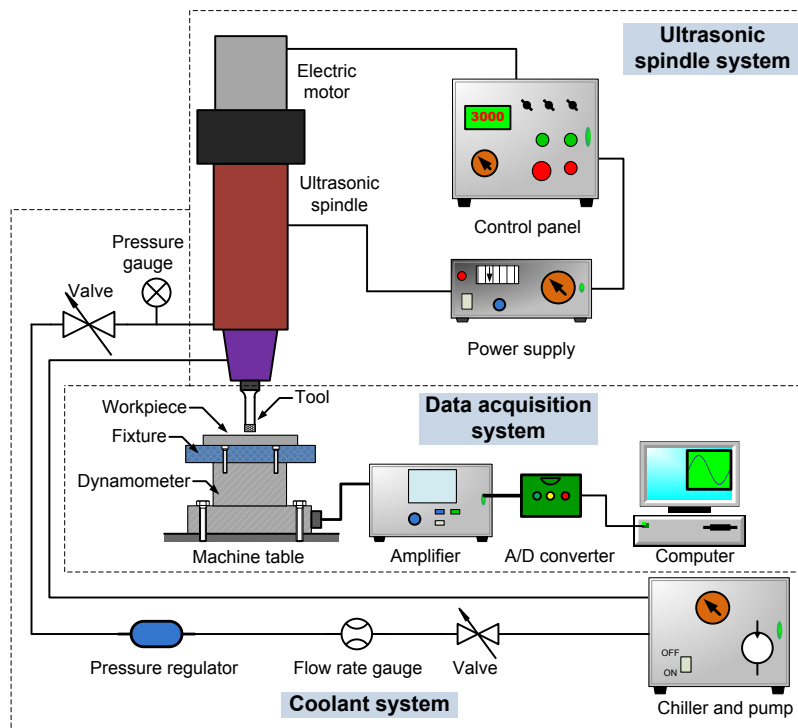
A typical RUM experiment set-up is shown in Figure 2.11. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system comprised an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converted low frequency (60 Hz) electrical supply into high frequency (20 kHz) AC output. This AC output was converted into mechanical vibrations by the crystal converter in the ultrasonic spindle. A diamond core drill was used to drill the silicon workpiece. The coolant system mainly included a refrigerated recirculator (including chiller, pump, and container), pressure regulator, flow rate gauge, pressure gauge, and valves. A refrigerated recirculator could generate cold water and pumped it to the ultrasonic spindle to keep the ultrasonic spindle cool. The cold water was also injected into the tool and workpiece surface to keep the cutting tool and silicon workpiece cool [34].

2.6.4 Experimental investigations

Important input variables include ultrasonic power, tool rotation speed, and feedrate. Important output variables include cutting force and edge chipping. Cong et al., [34] reported their investigations on edge chipping and cutting force in RUM of silicon. The outer and inner diameters of the tool were 9.53 mm and 8 mm, respectively, and the tuning length was 45 mm.

The size of the diamond abrasives was mesh 140/170. Higher tool rotation speed and ultrasonic power, and lower feedrate lead to smaller edge chipping thickness. Higher tool rotation speed and ultrasonic power, and lower feedrate lead to smaller cutting force. Large edge chipping is almost always accompanied by a higher cutting force.

Figure 2.11 System set-up of rotary ultrasonic machining (after [34]).



2.7 Conclusion remarks

Silicon based solar panels or other silicon workpieces have been drilled by laser drilling, microwave drilling, electrode discharge machining (EDM), ultrasonic vibration assisted drilling, and rotary ultrasonic machining (RUM). Table 2.2 compares these five methods. The table compares the hole diameter range, tool type, machine movement, and tool-workpiece contact, power consumption. Effects of some process parameters on certain output variables have been studied experimentally for these processes. The experimental investigations reviewed in this

paper are summarized in Table 2.3. The Table clearly shows that studies on many effects have not been reported yet.

Table 2.2 Comparison of five drilling methods.

	Laser	EDM	Microwave drilling	UV-A drilling	RUM
Hole diameter	30 - 100 μm (percussion) > 100 μm (trepanning)	< 1 mm	1 - 10mm	1 μm - 10 mm	3.2 - 28.6 mm
Contact	No	No	Yes	Yes	Yes
Tool type	-	Tungsten, cemented carbide	Tungsten	Tungsten carbide	Diamond grinding wheel
Movement	No	Rotation, feeding	Insertion, slow rotation	Fast rotation	Rotation,
Power	High	High	Medium	Low	Low

Table 2.3 Summary of reported experimental investigations on silicon drilling.

	Laser	EDM	Microwave drilling	Ultrasonic	RUM
Hole diameter	✓	✓		✓	
Drilling rate	✓				
MRR		✓			
Tool wear		✓		✓	
Hole surface roughness		✓			
Hole quality				✓	✓
Cutting force					✓

References

- [1] International Energy Agency, 2009, “Key world energy statistics”, http://www.iea.org/textbase/nppdf/free/2009/key_stats_2009.pdf.
- [2] Withagen, C., 1994, “Pollution and exhaustibility of fossil fuels, Resource and Energy”, Economics, 16(3), pp. 235-242.
- [3] Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D., 2006, “Environmental, economic,

- and energetic costs and benefits of biodiesel and ethanol biofuels”, PNAS, 103(30), pp. 11206-11210.
- [4] DOE/EIA, 2009, “Annual Energy Review 2008”, <http://www.eia.doe.gov/aer/pdf/aer.pdf>.
 - [5] Gail F., 2009, “Solar manufacturing: the sun always rises”, <http://www.smtonline.com>, January/February 2009, 3, Editor’s view.
 - [6] Stolberg, K.P., Kremser, B., Friedel, S., Atsuta, Y., 2009, “Systematic optimisation of process parameters in laser drilling of 200 μm photovoltaic silicon wafers using new kind of nanosecond IR lasers”, Journal of Laser Micro/Nanoengineering, 4(3), pp. 231—233.
 - [7] Gee, J.M., Schubert, K., Basore, P.A., 1993, “Emitter wrap-through solar cell”, Proceeding of the 23rd IEEE Photovoltaic Specialists Conference, May 10-14, Louisville, KY, USA.
 - [8] Van Kerschaver, E., Beaucarne, G., 2006, “Back-contact solar cells: A review”, Progress in Photovoltaics: Research and Applications, 14(2), pp.107-123.
 - [9] Grohe, A., Knorz, A., Nekarda, J., Jager, U., Mingirulli, N., Preu, R., 2009, “Novel laser technologies for crystalline silicon solar cell production”, Proceeding of the SPIE - The International Society for Optical Engineering, Jan. 28-29, San Jose, CA, USA.
 - [10] Schoonderbeek, A., Stute, U., Ostendorf, A., Grischke, R., Engelhart, P., Meyer, R., Brendel, R., 2006, “Laser technology for cost reduction in silicon solar cell production”, Proceeding of the 25th International Congress on Applications of Laser and Electro-Optics, Oct. 30-Nov. 2, Scottsdale, AZ, USA.
 - [11] Rand, J.A., 2008, “Solar cell design for manufacturing, National renewable energy laboratory”, <http://www.nrel.gov/docs/fy08osti/43228.pdf>.
 - [12] Harder, N.P., Hermann, S., Merkle, A., Neubert, T., Brendemühl, T., Engelhart, P., Meyer, R., Brendel, R., 2008, “Laser-processed high-efficiency silicon RISE-EWT solar cells and

- characterisation”, Proceeding of the 3rd Sino-German Symposium The Silicon Age: Silicon for Microelectronics, Photonics and Photovoltaics, Jun. 9-14, Hangzhou, China.
- [13] Mayerhofer, R., Müllers, L., Becker A., 2006, “Laser micro-processing in solar cell production”, Proceeding of the IEEE 4th World Conference on Photovoltaic Energy Conversion, WCPEC-4, May 7-12, Waikoloa, HI, USA, 1, pp. 1115-1118.
- [14] Miyamoto, I., Asada, S., Sano, T., Ohmura, E., 2001, “High speed drilling of thin silicon wafer by UV laser”, Proceeding of International Congress on Applications of Lasers and Electro-Optics, Oct. 15-18, Jacksonville, FL, USA, pp. 1612-1619.
- [15] Chen, M.F., Hsiao, W.T., Ho, Y.S., Huang, K.C., Tseng, S.F., Chen, Y.P., 2008, “Investigation of laser micro-drilling for silicon wafer substrate”, <http://rnd2.ncue.edu.tw/ezcatfiles/b004/img/img/316/97-1-17paper.doc>.
- [16] Rainer P, 2002 Comparison excimer laser – solid state laser, Lambda Physok AG, pp. 1-10.
- [17] Zhu, X.S., Choi, J.W., Cole, R., Ahn, C.H., 2002, “A new laser micromachining technique using a mixed-mode ablation approach”, Proceeding of the IEEE Micro Electro Mechanical Systems (MEMS), Jan. 20-24, Las Vegas, NV, USA.
- [18] Yokotani, A., Mukumoto, T., Kanamitsu, Y., Fukumoto, H., Kurosawa, K., 2005, “Time-resolving image analysis of drilling of thin silicon substrates with femtosecond laser ablation”, Japanese Journal of Applied Physics, Part 1 (Regular Papers, Short Notes & Review Papers), 44(11), pp. 7998-8003.
- [19] Jiao, L., Ng, E.Y.K., Wee, L.M., Zheng, H., 2009, “Parametric study of femtosecond pulses laser hole drilling of silicon wafer”, Advanced Materials Research, 74, pp. 273-277.
- [20] Geng, N., Fu, X., Li, H.X., Ni, X.C., Hu, X.T., 2007, “Effects of laser parameters in the micromachining of silicon by femtosecond pulse laser”, Key Engineering Materials, 339,

pp. 136-140.

- [21] Alexander, D.R., Mihulka, B., Doerr, D., 2000, "Femtosecond laser drilling of high aspect ratio 1 μm holes in silicon", Proceeding of the SPIE - The International Society for Optical Engineering, Apr. 22-26, Taos, NM, USA.
- [22] Chien, C.Y., Gupta, M.C., 2005, "Pulse width effect in ultrafast laser processing of materials", Applied Physics A (Materials Science Processing), 81(6), pp. 1257-1263.
- [23] Asada, S., Sano, T., Miyamoto, I., 2000, "High efficient microdrilling of silicon wafer using excimer laser", Proceeding of SPIE - The International Society for Optical Engineering, Jun. 14-16, Omiya, Japan.
- [24] Yamashita, Y., Hosono, T., Hidai, H., Tokura, H., "Processing of silicon by direct irradiation of laser beam transmitted through optical fiber", Journal of the Japan Society of Precision Engineering, 74(5), pp. 463-467.
- [25] Matsumura, T., Nakatani, T., Yagi, T., 2007, "Deep drilling on a silicon plate with a femtosecond laser: experiment and model analysis", Applied Physics A: Materials Science & Processing, 86(1), pp. 107-114.
- [26] Jerby, E., Dikhtyar, V., Aktushev, O., Groszlick, U., 2002, "The microwave drill", Science, 298, pp. 587-589.
- [27] Song, X.Z., Meeusen, W., Reynaerts, D., Brussel, H.V., 2000, "Experimental study of micro-EDM machining performances on silicon wafer, In Micromachining and Microfabrication Process Technology VI", Proceeding of SPIE, 4174, pp. 331-339.
- [28] Uno, Y., Okada, A., Okamoto, Y., 1997, "High efficiency penetration boring of single crystalline silicon ingot by EDM", Journal of the Japan Society of Precision Engineering, 63(12), pp. 1725-1729.

- [29] Egashira K., Mizutani K., 2002, "Micro-drilling of monocrystalline silicon using a cutting tool", *Precision Engineering*, 26, pp. 263-268.
- [30] Ramulu, M., See, H.W., Wang, D.H., 1990, "Machining of Ceramic Composite TiB sub 2/SiC by Spark Erosion", *Manufacturing Review*, 3(22), pp. 123-129.
- [31] Reynaerts, D., Heeren, P.H., Brussel, H.V., 1997, "Microstructuring of silicon by electro-discharge machining (EDM)- part I: theory", *Sensors and Actuators A: Physical*, 60(1-3), pp. 212-218.
- [32] Reynaerts, D., Meeusen, W., Brussel, H.V., 1998, "Machining of three-dimensional microstructures in silicon by electro-discharge machining", *Sensors and Actuators A*, 67, pp. 150-165.
- [33] Tsui, C.Y., Lu, M.C., Wu, C.C., Huang, C.F., 2008, "Drilling of microholes on silicon wafer with ultrasonic workpiece holder", *Proceeding of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2008*, August 3-6, Brooklyn, NY, USA.
- [34] Cong, W.L., Feng, Q., Pei, Z.J., Deines, T., Treadwell, C., 2010, "Edge Chipping in Rotary Ultrasonic Machining of Silicon: A Study Using Design of Experiment and Finite Element Analysis", submitted to *Machining Science and Technology*.

Chapter 3 - Literature Review - Dry Machining

Paper title:

Dry machining using vortex-tube generated cold air as coolant: a literature review

Published in:

Proceedings of the ASME 2008 International Manufacturing Science & Engineering Conference (MSEC-2008), October 7-10, 2008, Evanston, IL, USA

Authors' names:

Cong, W.L., and Pei, Z.J.

Authors' affiliations:

Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

Abstract

This paper reviews the literature on dry machining with VT cooling (using vortex-tube generated cold air as coolant). It presents reported experimental results on effects of VT cooling on cutting force, cutting temperature, tool wear, surface roughness, and residual stress. It also points out areas where VT cooling applications have not been reported and potential directions for future research.

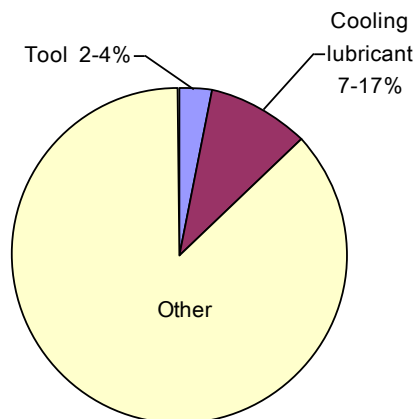
Keywords: Coolant; Cutting, Cutting fluid, Cutting force, Cutting temperature, Grinding, Machining, Milling, Tool wear, Turning, Vortex tube.

3.1 Introduction

Machining plays a central role in modern manufacturing, and its cost amounts to more than 15% of the total value of all products of the entire manufacturing industry [1].

Deployment of cooling lubricant counts for about 7-17% of the total cost of machining. In comparison, tool costs account for approximately 2-4%, as shown in Figure 3.1 [2].

Figure 3.1 Costs in machining (after [2]).



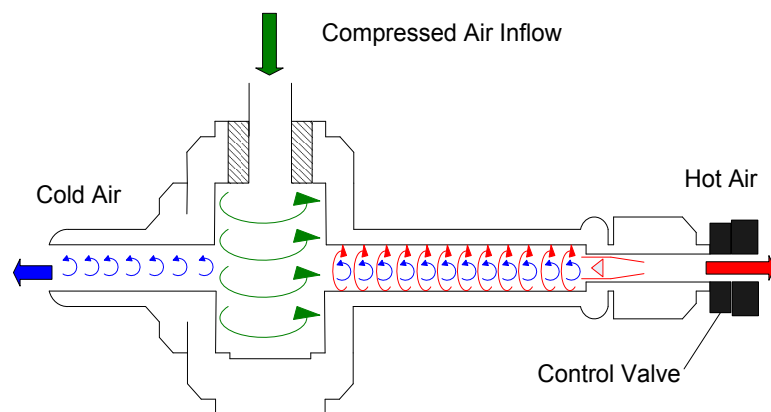
Due to concern on the environment, dry machining (machining without direct contact between coolant fluid and cutting zone) is becoming increasingly more popular. The advantages of dry machining include: less pollution to the environment, reduced cost in disposal and cleaning of chips (swarf), and being harmless to skin [3].

Table 3.1 summaries reported methods used for dry machining. Among them is VT cooling (using vortex tube to generate cold air as coolant). In the literature, there is no review paper available on VT cooling.

Table 3.1 Reported methods of dry machining.

Method	Description	Reference
Cryogenic cooling	A stream of cryogenic coolant flows through a conduit inside the tool.	[4]
Internal cooling by vaporization	A vaporizable liquid is introduced inside the shank of the tool and is vaporized on the underside surface of the insert.	[3]
Thermoelectric cooling	A retainer made of highly heat conductive material is in surface-to-surface contact with a cutting tool, forming a couple of thermoelectric elements. When an electric current is passed through the thermoelectric elements, a cold junction (located at the contact surface between the tool and the retainer) is produced to cool the tool.	[5]
Under cooling	Coolant flows through channels located under the insert, without contact with the cutting zone.	[6]
Vortex tube cooling	Cold air generated by a vortex tube is used as coolant.	[7]

Figure 3.2 Vortex tube (after [7]).



A vortex tube, as illustrated in Figure 3.2, is a simple mechanical device without any moving components. It separates a stream of compressed air into two branches: a hot component and a cool component [4]. With nothing more than a few pieces of plumbing and a source of compressed air, one can build a simple device to attain moderately low temperatures [5]. Compressed air is injected into a swirl chamber and accelerates to a high rate of rotation. Due to the conical nozzle at the end of the tube, only the outer shell of the compressed gas is allowed to escape at that end. The remainder of the air is forced to return in an inner vortex of reduced diameter within the outer vortex [6]. When compressed air is released into the tube through the vortex generator, you get hot air out of one end of the tube and cold air out the other. A small valve in the hot end, adjustable with the handy control valve, is used to control the air volume and temperature released from the cold end [7].

The purpose of this paper is to provide a literature review on dry machining using vortex-tube generated cold air as coolant. This paper has seven sections. Following this introduction section, Sections 3.2 to 3.6 discuss the effects of VT cooling on cutting forces, cutting temperature, tool wear, surface roughness, and residual stress, respectively. Section 3.7 contains concluding remarks.

3.2 Effects on cutting forces

Nguyen and Zhang [11] studied the effects of vortex tube cooling on cutting force in surface grinding of steels.

Their experiments were performed on a surface grinding machine (Minini Junor 90 CNC-M286). The workpiece material was 1045 carbon steel. The grinding wheel used was a CBN wheel (CBN-BWA60MVA1). The grinding wheel speed was 23 m/s and the work speed was 400 mm/min. Compressed air at 600 kPa with a flow rate of 150 SCFM (4248 L/min) was

ejected through a vortex tube (VT) to generate cold air. The temperature at outlet of the nozzle was -20 °C. As a comparison, grinding tests under other cooling conditions were also conducted: (a) grinding fluid, consisting of Noritake SA-02 (1:60), at 20 °C with the flow rate of 14.5 l/min; and (b) atmospheric dry air at 20 °C. These experimental and cooling conditions are summarized in Table 3.2 and Table 3.3, respectively.

Their results are presented in Figure 3.3 and Figure 3.4. Tangential force, F_x , was the grinding force in the direction parallel to the ground surface; normal force, F_z , was the grinding force in the direction perpendicular to the ground surface. It can be seen that VT cooling (using cold air generated by vortex tube as coolant) could reduce grinding force. It is noted that this result is true only for low material removal rates. For high material removal rates, VT cooling did not show much effect on reduction of cutting force.

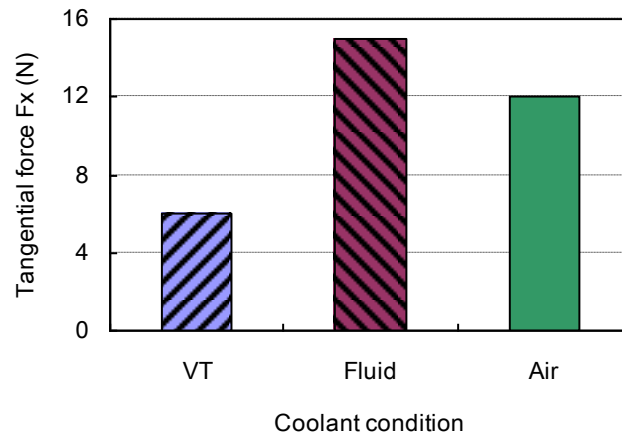
Table 3.2 Experimental conditions used by Nguyen and Zhang [11].

Parameter	Value
Grinding machine	CNC-M286
Workpiece material	1045 carbon steel
Grinding wheel	CBN-BWA60MVA1
Grinding wheel speed, v , (m/s)	23
Work speed, f_w , (mm/min)	400
Depth of cut, d , (μm)	5; 10; 15; or 20
Air pressure going into VT (kPa)	600
Air flow rate going into VT (L/min)	4248
VT cold air temperature (°C)	-20

Table 3.3 Cooling conditions used by Nguyen and Zhang [11].

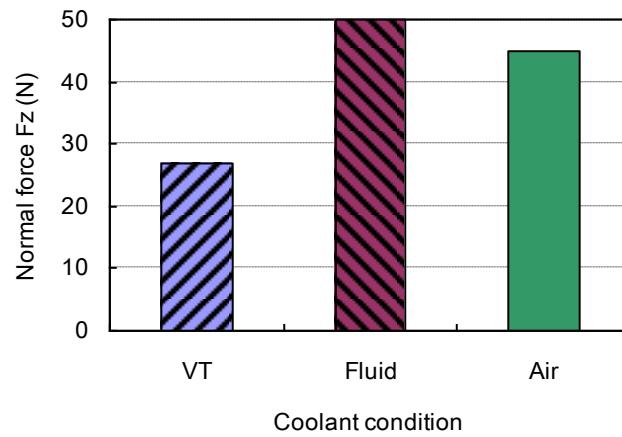
	Temperature (°C)	Flow rate (L/min)
VT cold air	-20	
SA-02 grinding fluid	20	14.5
Atmospheric dry air	20	

Figure 3.3 Tangential grinding force (after [11]).



$$v = 23 \text{ m/s}; f_w = 400 \text{ mm/min}; d = 10 \text{ }\mu\text{m}$$

Figure 3.4 Normal grinding force (after [11]).



$$v = 23 \text{ m/s}; f_w = 400 \text{ mm/min}; d = 10 \text{ }\mu\text{m}$$

3.3 Effects on cutting temperature

Liu et al. [14,15] studied effects of VT cooling on cutting temperature in turning. Workpiece material was hypereutectic silicon-aluminum alloy (A390).

Their experiments were conducted on a manual lathe using tungsten carbide tools. Two cutting speeds (3.1 and 5 m/s), and two feedrates (0.055 and 0.115 mm/rev) were used. Depth of cut was kept at 2 mm. Two settings of VT cooling were tested. The first setting (referred to as VT_MT) provided the least volume of cold air (at a flow rate of $9.43 \times 10^{-4} \text{ m}^3/\text{s}$) and the lowest possible temperature (-20°C). The second setting (VT_MF) was to release the maximum volume of cold air (at a flow rate of $1.32 \times 10^{-2} \text{ m}^3/\text{s}$) and a temperature of 10°C . A brass nozzle, with an inner diameter of 6.35 mm, was attached to the cold end of the vortex tube about 30 mm away from the cutting tip. Tool temperatures were monitored by thermocouples [13]. These experimental and cooling conditions are also summarized in Table 3.4 and Table 3.5.

Table 3.4 Experimental conditions used by Liu and Chou [13].

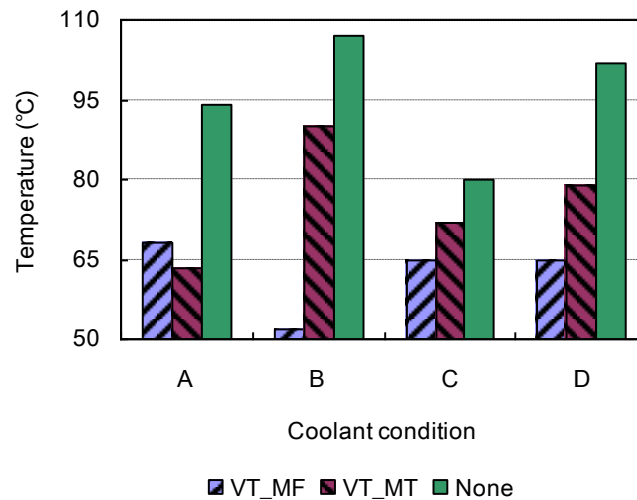
Parameter	Value
Machine	Lathe
Tool material	Tungsten carbide
Workpiece material	A390 (Al-Si alloy)
Cutting speed, v , (m/s)	3.1; or 5.0
Feedrate, f , (mm/rev)	0.055; or 0.115
Depth of cut, d , (mm)	2
Nozzle diameter (mm)	6.35

Table 3.5 VT cooling conditions used by Liu and Chou [13].

	Temperature ($^\circ\text{C}$)	Flow rate (L/min)
VT_MT	-20	57
VT_MF	10	79

Their results are summarized in Figure 3.5. With VT cooling, the minimum-temperature setting (VT_MT) is more effective than the maximum-flow setting (VT_MF) [12]. They also observed that effects of VT cooling on temperature reductions decreased with the increase of the cutting speed and feedrate. Furthermore, they did not see any direct correlations between tool temperature decrease and tool wear reduction [13].

Figure 3.5 Cutting temperature under different coolant conditions (after [13]).



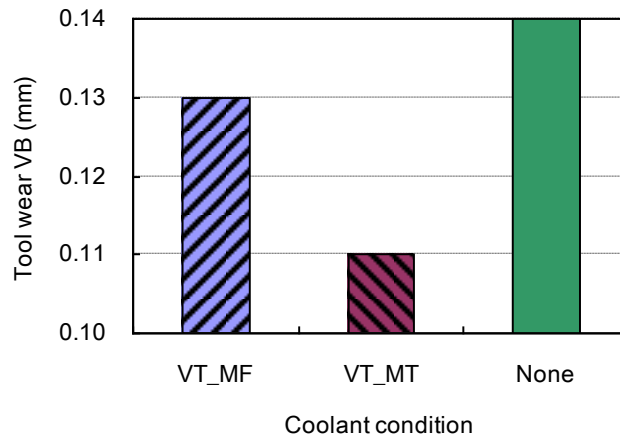
Experiments by Nguyen and Zhang [11] showed that cold air could be used to suppress surface burning under certain material removal rates. Their experimental conditions are summarized in Table 3.2 and Table 3.3.

3.4 Effects on tool wear

Liu et al. [12] studied the effects of VT cooling on tool wear when turning of A390 alloy using tungsten carbide tools. Details on the experimental conditions are presented in Table 3.4 and Table 3.5 already. Tool wear was regularly measured during machining by optical microscopy [13].

Figure 3.6 shows the results on tool flank wear-land (VB). The tool wear with VT_MT is about 12% less than that without VT cooling. However, effects of VT cooling on tool wear depended on cutting conditions with the combination of high speed and low feedrate being the most effective [12]. When both cutting speed and feedrate were low, VT cooling has virtually no effect [12]. Additionally, the minimum temperature setting (VT_MT) was more effective in tool wear reductions than the maximum flow setting (VT_MF) under most cutting conditions [13].

Figure 3.6 Tool wear under different cooling conditions (after [12]).



$v = 5 \text{ m/s}$, $f = 0.055 \text{ mm/rev}$, time $t = 7 \text{ min}$

Liu and Hu [14] compared the tool lives with and without VT cooling in turning of J-55 steel. The tool material was tungsten carbide YT15 (85% WC, 15% Co). The cutting speed was 4.91 m/s, feedrate 0.11 mm/rev, depth of cut 0.5 mm. The compress air going into vortex tube had a pressure of 0.3 MPa and a temperature of 20 °C. The experimental conditions are also summarized in Table 3.6.

Table 3.6 Experimental conditions used by Liu and Hu [14].

Parameter	Value
Tool material	YT15
Workpiece material	J-55 steel
Vortex tube model	QL-8
Cutting speed, v , (m/s)	4.91
Feedrate, f , (mm/rev)	0.11
Depth of cut, d , (mm)	0.5
Cutting time, t , (s)	120
Air pressure going into VT (MPa)	0.3
Air temperature going into VT (°C)	20

Figure 3.7 is a comparison of tool wear on the tool rake surface. The tool wear was measured by KB, the width of the crater on the rake surface. It can be seen that the tool wear on the rake surface with VT cooling was smaller than that without VT cooling.

Figure 3.7 Tool wear with and without VT cooling (after [14]).

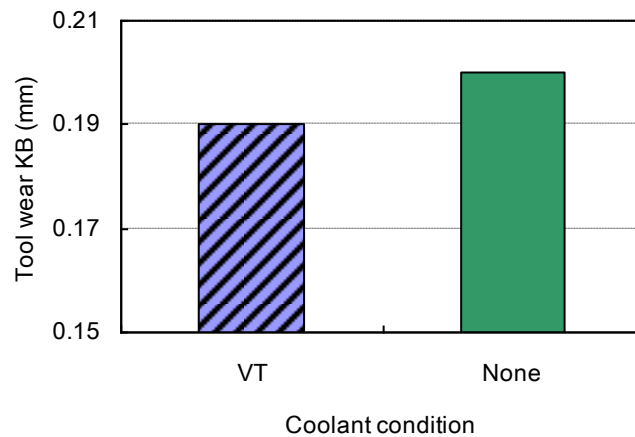
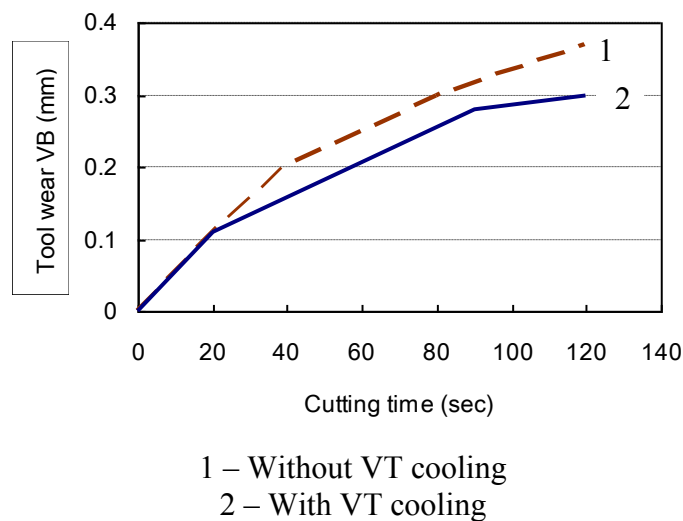


Figure 3.8 shows two curves of tool wear on the tool flank surface, VB, versus cutting time. The tool flank wear VB increased with cutting time. It is obvious that the tool wear on the flank surface with VT cooling was smaller than that without VT cooling.

Figure 3.8 Relationship between tool wear and cutting time (after [14]).



Su et al. [15] studied the effects of cold air cooling on tool wear in turning of Inconel 718 nickel-base super alloy and milling of AISI D2 tool steel. They did not use vortex tube to generate the cold air. Instead, they used a composite refrigeration method (consisting of vapor-compression refrigeration system and semiconductor refrigeration system) to produce cold air. Their experimental conditions are shown in Table 3.7 and cooling conditions are shown in Table 3.8

Table 3.7 Turning experimental conditions used by Su et al. [15].

Parameter	Value
Machine	CA630 lathe
Workpiece material	Inconel 718
Tool material	Coated carbide (KC5010)
Cutting Speed, v , (m/min)	76
Feedrate, f , (mm/rev)	0.1
Depth of cut, d , (mm)	0.5
Cold air pressure (MPa)	0.6
Cold air flow rate (L/min)	120
Cold air temperature (°C)	-20

Table 3.8 Milling experimental conditions used by Su et al. [15].

Parameter	Value
Machine	Mikron UCP 710 five-axes vertical machining center
Workpiece material	Tool steel AISI D2
Tool material	Coated carbide (K30)
Cutting Speed, v , (m/min)	175
Feedrate, f , (mm/tooth)	0.08
Axial depth of cut (mm)	4
Radial depth of cut (mm)	0.4
Cold air pressure (MPa)	0.6
Cold air flow rate (L/min)	120
Cold air temperature (°C)	-20

Their results are summarized in Figure 3.9 and Figure 3.10. For both cases, application of cold air cooling resulted in a drastic reduction in tool wear. The increase in tool life was 78% when turning of Inconel 718, and 130% when milling of tool steel AISI D2.

Figure 3.9 Nose wear curves when turning of Inconel 718 (after [15]).

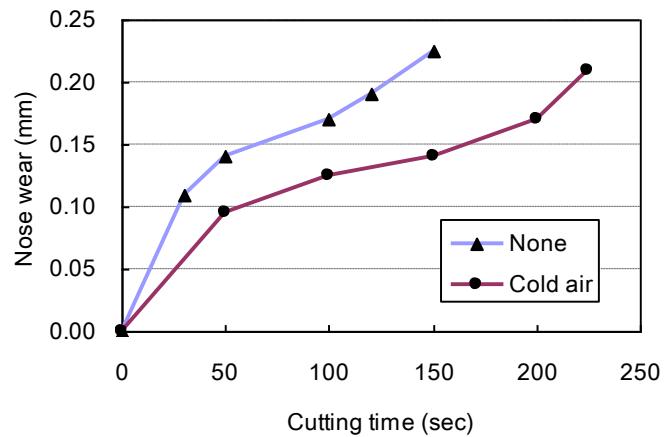
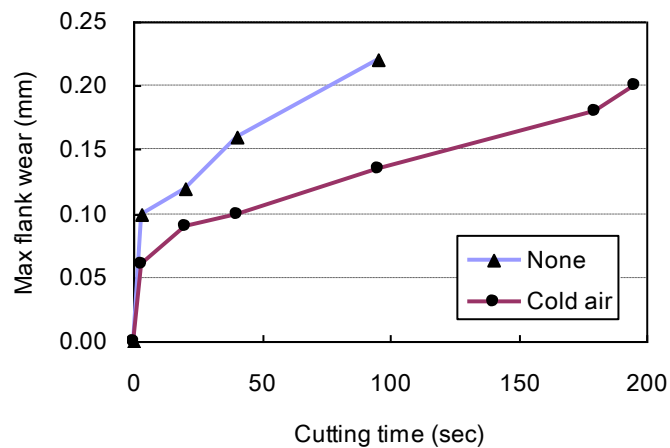


Figure 3.10 Max flank wear curves when milling of tool steel AISI D2 (after [15]).



Liu and Chou [12] reported that VT cooling might reduce tool wear in turning of silicon-aluminum alloy A390, depending upon machining conditions. They reported that the outlet temperature of VT cold air was more critical than its flow rate. Their experimental conditions are presented in Table 3.4 and Table 3.5.

3.5 Effects on surface roughness

Su et al. [15] studied the effects of cold air cooling on surface roughness in turning of Inconel 718 and milling of tool steel AISI D2. Details on the experimental conditions are presented in Table 3.7 and Table 3.8 already.

Their results are summarized in Figure 3.11 and Figure 3.12. When turning of Inconel 718, surface roughness (R_a) obtained when using cold air cooling was lower than that without using cold air cooling. When milling of tool steel AISI D2, the effects of cold air cooling were not consistent. Surface roughness with cold air cooling was lower than without cold air cooling at the beginning of the cutting (cutting time < 50 seconds), but higher after cutting time exceeded 50 seconds.

Figure 3.11 Surface roughness when turning of Inconel 718 (after [15]).

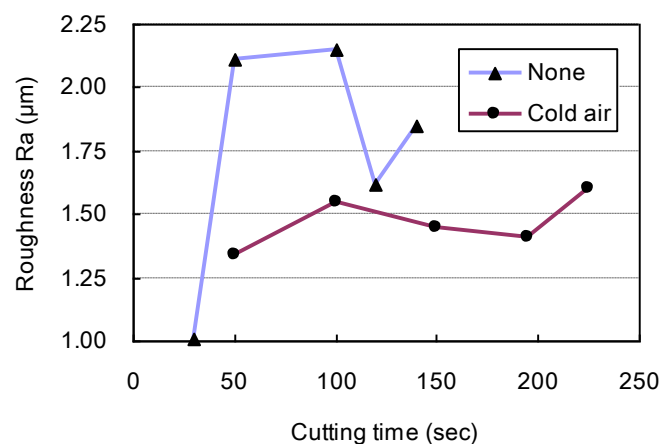
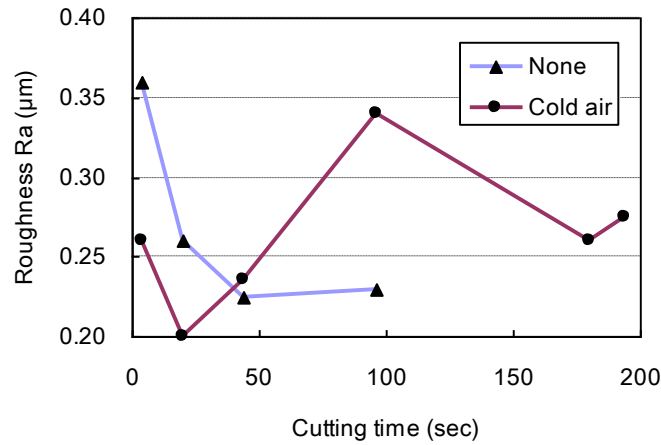


Figure 3.12 Surface roughness when milling of tool steel AISI D2 (after [15]).



Nguyen and Zhang [11] studied effects of VT cooling on surface roughness in surface grinding of carbon steel 1045 with a CBN wheel. Details of experimental and cooling conditions have been presented in Table 3.2 and Table 3.3.

Their results are summarized in Figure 3.13. Surface roughness was measured in transverse grinding direction. When depth of cut was small ($d = 5 \mu\text{m}$), surface roughness with VT cooling was worse than that with coolant fluid and also worse than that without cooling. When depth of cut was large ($d = 10$ or $15 \mu\text{m}$), surface roughness with VT cooling was worse than that with coolant fluid but better than or equivalent to that without cooling.

Choi et al. [16] studied effects of VT cooling on surface roughness in cylindrical grinding of the spindle shaft materials (SCM4 and SCM21) with a CBN wheel.

Their experiments were conducted on a CNC cylindrical grinder. The compressed cold air had a pressure of 4 kgf/cm^2 (0.4 MPa), a temperature of -10°C . Two velocity values were used: 40 and 80 m/s. The nozzle for the cold air had two diameters: 9.3 mm and 12.3 mm. Their experimental conditions are in Table 3.9 and Table 3.10.

Figure 3.13 Surface roughness when grinding of tool steel (after [11]).

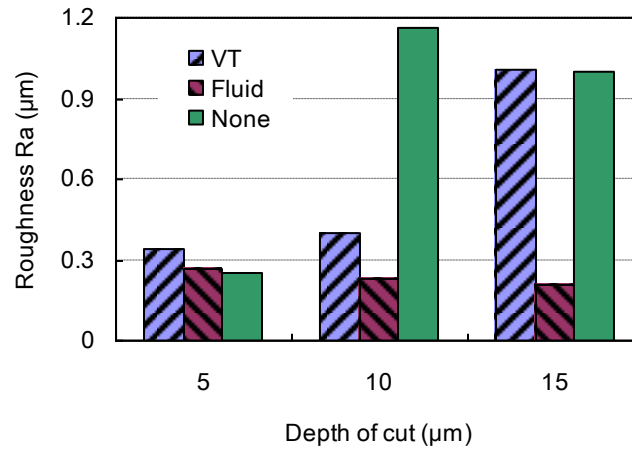


Table 3.9 Experimental conditions used by Choi et al. [16].

Parameter	Value
Grinding machine	CNC cylindrical grinder
Grinding wheel	CBN-B80H150VC
Workpiece	Spindle shaft material SCM4 and SCM21
Depth of cut (μm/s)	3; 5; 10; 20; or 30
Wheel speed (m/s)	35
Workpiece speed (m/min)	18

Table 3.10 Cooling conditions used by Choi et al. [16].

Parameter	Value
Coolant fluid	Emulsion (4%)
VT cooling	
Pressure of cold air (kgf/cm ²)	4
Temperature of cold air (°C)	−10
Velocity, v, (m/s)	40; or 80
Nozzle diameter, Φ, (mm)	9.3; or 12.3

Their results are shown in Figure 3.14 and Figure 3.15. Figure 3.14 compares the surface roughness using VT cooling and that using coolant fluid when the depth of cut was 10 μm. It can be seen that the surface roughness using VT cooling was worse than that with coolant fluid. The same trend was seen for other values of depth of cut.

Figure 3.15 shows surface roughness results under three different VT cooling conditions. Surface roughness was the lowest with higher velocity and smaller nozzle diameter.

Figure 3.14 Surface roughness with VT cooling and coolant fluid when grinding of spindle shaft material (depth of cut was 10 μm) (after [16]).

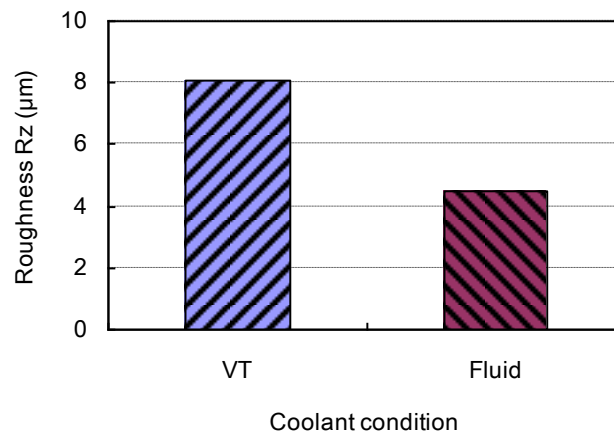
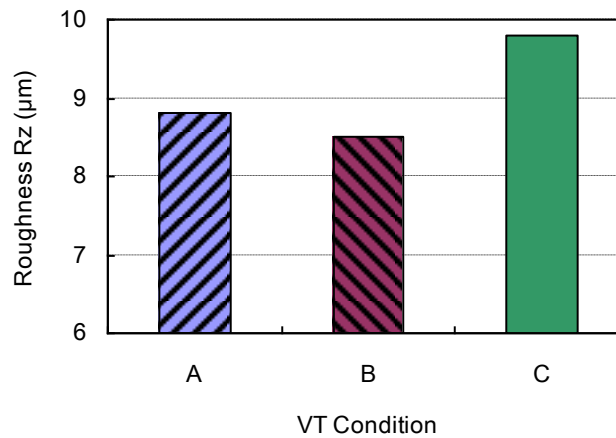


Figure 3.15 Surface roughness under different VT cooling conditions when grinding of spindle shaft material (depth of cut was 10 μm) (after [16]).



- A. $v = 40 \text{ m/s}$, $\Phi = 9.3 \text{ mm}$
- B. $v = 80 \text{ m/s}$, $\Phi = 9.3 \text{ mm}$
- C. $v = 40 \text{ m/s}$, $\Phi = 12.3 \text{ mm}$

Nguyen and Zhang [11] conducted grinding tests to compare the surface roughness obtained when using coolant fluid and that when using VT cooling. They found that surface roughness using coolant fluid was better than that using VT cooling. Their experiment conditions are shown in Table 3.2 and Table 3.3 [11]. Dudley also reported that surface roughness using coolant fluid was better than that with compressed cold air [8].

3.6 Effects on residual stress

Nguyen and Zhang [11] studied effects of VT cooling on residual stress in surface grinding of carbon steel 1045 with a CBN wheel. Details of experimental conditions are presented in Table 3.2 and Table 3.3.

Their results are summarized in Figure 3.16 and Figure 3.17. It can be seen that there was no significant difference between the residual stress produced with coolant fluid and that with VT coolant.

Figure 3.16 Longitudinal residual stress (after [11]).

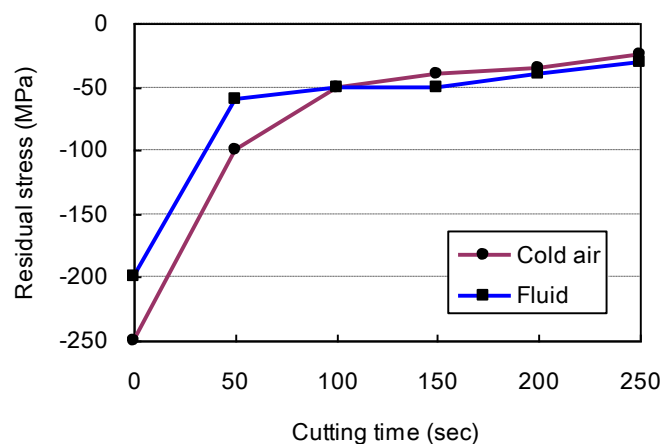
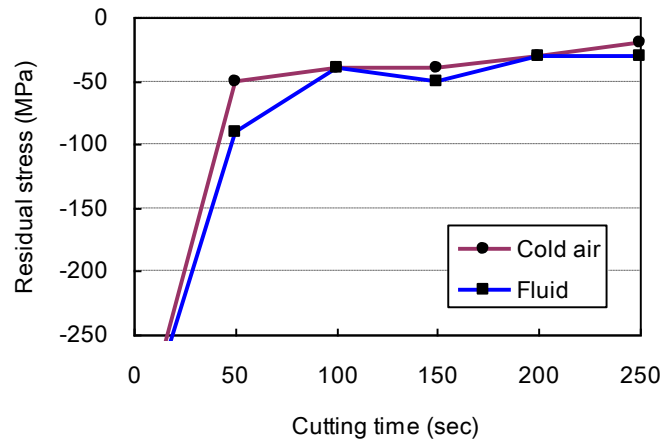


Figure 3.17 Transverse residual stress (after [11]).



Choi et al. [16] studied effects of VT cooling on residual stress in cylindrical grinding of the spindle shaft materials (SCM4 and SCM21) with a CBN wheel. Details of experimental conditions are shown in Table 3.9 and Table 3.10.

Their results are summarized in Figure 3.18 and Figure 3.19. Figure 3.18 clearly shows that, when grinding of SCM4, residual stress with coolant fluid was lower than that with VT coolant. However, as shown in Figure 3.19, when grinding of SCM21, the situation was more complicated. Between the two VT cooling conditions, the compressive residual stress with higher velocity and smaller nozzle diameter had smaller absolute value than that with lower velocity and larger nozzle diameter. Coolant type (VT coolant versus coolant fluid) and depth of cut had interaction effects on residual stress. When depth of cut was below 15 μm , the compressive residual stress with the coolant fluid was greater (in absolute value) than that with CT cooling. However, when depth of cut was 30 μm , the compressive residual stress with CT cooling was greater (in absolute value) than that with coolant fluid. In other words, when depth of cut was changed from 3 to 30 μm , the residual stress with VT cooling had much larger changes than that with coolant fluid.

Figure 3.18 Residual stress when grinding of SCM4 (after [16]).

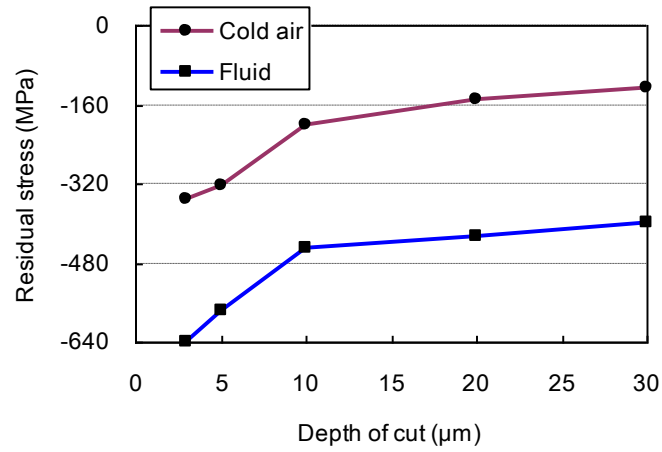
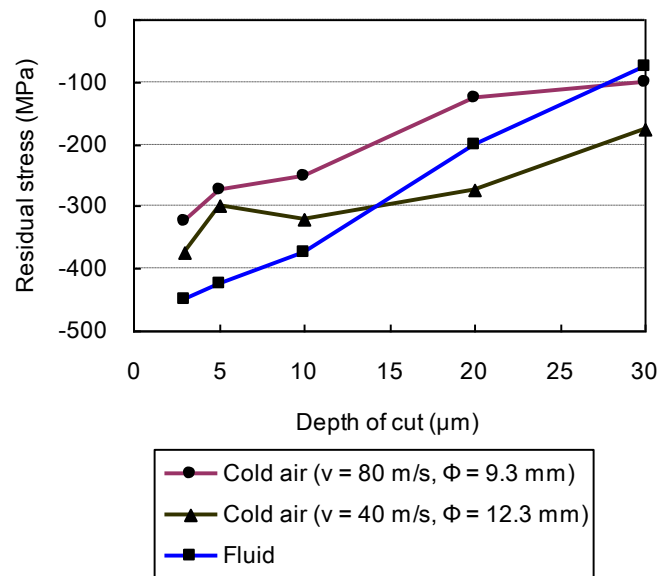


Figure 3.19 Residual stress when grinding of SCM21 (after [16]).



3.7 Concluding remarks

VT cooling (using vortex tube generated cold air as coolant) has been reported in several machining processes: turning, milling, and grinding. Reported applications of VT cooling are summarized in Table 3.11.

It has been reported that, comparing to conditions where no coolant was used, VT cooling could reduce cutting force, cutting temperature, tool wear, and surface roughness. However, CT cooling was less effective than coolant fluid in reducing cutting force, temperature, tool wear, and surface roughness.

It is noted that there is no reports on applications of VT cooling in drilling operations. Furthermore, many types of workpiece materials have not been tested with VT cooling. Applying VT cooling in processes such as drilling and to materials such as ceramics and composites can be potential directions for future research.

Table 3.11 Report applications of VT cooling

Process	Workpiece material	Reference
Turning	Aluminum-silicon alloy A390	[13]
	Steel J-55	[14]
	Inconel 718	[15]
Milling	Tool steel AISI D2	[15]
Grinding	Carbon steel 1045	[11]
	Spindle shaft material SCM4 and SCM21	[16]

References

- [1] Merchant, M. E., 1998, "Interpretive Look at 20th Century Research on Modeling of Machining," *Machining Science and Technology*, **2**(2), pp. 157-163.
- [2] Klock, F., and Eisenblatter, G., 1997, "Dry Cutting," *Annals of the CIRP*, **46**(2), pp. 519.

- [3] Sreejith, P. S., and Ngoi, B. K. A., 2000, "Dry Machining: Machining of the Future," *Journal of Materials Processing Technology*, **101**(1-3), pp. 287-291.
- [4] Ahlborn, B., Keller, J. U., Staudt, R., Treitz, G., and Rebhan, E., 1994, "Limits of Temperature Separation in a Vortex Tube," *Journal of Physics D: Applied Physics*, **27**(3), pp. 480-488.
- [5] "The 'Hilsch' Vortex Tube," <http://www.visi.com/~darus/hilsch/>
- [6] Wikipedia, "Vortex tube," http://en.wikipedia.org/wiki/Vortex_tube.
- [7] AiRTX, Company Web site, "How Vortex Tubes Work," http://www.airtxinternational.com/how_vortex_tubes_work.php.
- [8] Dudly, G. M., 1976, "Machining Tool having Internally Routed Cryogenic Liquid for Cooling Interface between Cutting Tool and Work Piece," U.S. Patent, No. 3 971 114.
- [9] Meyers, P. G., 1964, "Tool Cooling Apparatus," U.S. Patent, No. 3 137 184.
- [10] Ber, A., and Goldblatt, M., 1989, "Influence of the temperature gradient on the wear in turning tools," *Annals of the CIRP*, Vol. **38**(1), pp. 69-73.
- [11] Nguyen, T., and Zhang, L. C., 2003, "An Assessment of the Applicability of Cold Air and Oil Mist in Surface Grinding," *Journal of Materials Processing Technology*, **140**(1-3), pp. 224-230.
- [12] Liu, J., and Chou, Y. K., 2005, "Vortex-tube Cooling for Tool Wear Reduction in A390 Dry Machining," *World Tribology Congress III*, Washington D.C., WTC2005-64166.

- [13] Liu, J., and Chou, Y. K., 2007, "On Temperatures and Tool Wear in Machining Hypereutectic Al-Si Alloys with Vortex-Tube Cooling," *International Journal of Machine Tools & Manufacture*, **47**(3-4), pp. 635–645.
- [14] Liu, C.X., and Hu, R.S., 1997, "Cooling Air from Vortex Tube Applied to Tool Cooling," *Manufacturing Technology and Machine Tool*, **1**, pp. 30-31. (In Chinese).
- [15] Su, Y., He, N., Li, L., Iqbal, A., Xiao, M. H., Su, S., and Qiu, B. G., 2007, "Refrigerated Cooling Air Cutting of Difficult-to-Cut Materials," *International Journal of Machine Tools and Manufacture*, **47**(6), pp. 927-933.
- [16] Choi, H. Z., Lee, S. W., and Jeong, H. D., 2001, "A Comparison of the Cooling Effects of Compressed Cold Air and Coolant for Cylindrical Grinding with a CBN Wheel," *Journal of Materials Processing Technology*, **111**(1-3), pp. 265-268.

Chapter 4 - Silicon – A Study on Edge Chipping

Paper title:

Edge chipping in rotary ultrasonic machining of silicon

Published in:

International Journal of Manufacturing Research (2012), Vol. 7, No. 3, pp. 311-329

Authors' names:

Cong, W.L.¹, Feng, Q.¹, Pei, Z.J.¹, Deines, T.W.¹, and Treadwell, C.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

2. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

With the increase in demand of energy, more and more silicon-based solar panels are used to convert solar energy to electricity. In solar panel manufacturing, to increase the efficiency of solar cells, electrical contacts of the front side need to be connected to the back side of the panel. Therefore, holes of different sizes need to be drilled in silicon solar panels of certain designs. Because silicon has high brittleness and hardness, drilling of silicon solar panels using traditional drilling methods might lead to solar panel cracking and low tool life. Rotary ultrasonic machining (RUM) is one of the nontraditional drilling processes. It has been used to drill holes in many brittle materials. However, there is no report in the literature on RUM of silicon. This paper presents a study on edge chipping in RUM of silicon. Two-level three-factor full factorial design was employed to experimentally determine effects of input variables on edge chipping and cutting force. The experimentally determined relation between edge chipping and cutting force was compared with that obtained by finite element analysis. Higher tool rotation speed, higher ultrasonic power, and lower feedrate led to smaller edge chipping and low cutting force. An important influencing parameter on edge chipping is cutting force. Large edge chipping is almost always accompanied by higher cutting force.

Keywords: Cutting force, Edge chipping, Rotary ultrasonic machining, Silicon, Solar panel.

4.1 Introduction

With the development of global economics, more and more energy is needed. The world total energy supply has more than doubled from 1971 to 2007 [International Energy Agency, 2009]. Fossil fuels take more than 80% of the total energy supply in 2009 [International Energy Agency, 2009]. However, they are non-renewable and will not last forever. In addition, burning

of fossil fuels will emit green house gasses [Withagen, 1994; Hill, 2006]. Therefore, it is vital to use renewable energy sources including solar energy [Mayerhofer et al., 2006; DOE/EIA, 2009].

At present, a typical solar panel can utilize only about one sixth of the sunlight entering it. Challenges related to solar panels include improving the efficiency of solar cells and reducing the manufacturing cost of solar panels [Gail F., 2009]. In order to increase the efficiency of silicon-based solar cells, electrical contacts of the front side need to be connected to the back side of the panel. This requires drilling holes of different sizes on silicon panels of certain designs [Mayerhofer et al., 2006; Stonerg et al., 2009].

Several methods have been reported to drill silicon workpieces. Laser drilling was reported to drilling holes (in silicon) with diameters ranging from 30 to 100 μm . Larger holes were drilled by utilizing a relative movement between laser beam and workpiece. A shortcoming of laser drilling is the heat affected zone (HAZ) around the drilled hole [Yokotani et al., 2005; Stolberg et al., 2009; Miyamoto et al., 2001; Mayerhofer et al., 2006; Geng et al., 2007; Asada et al., 2000]. Electrical discharge machining was used to drill holes whose diameters were less than 1 mm [Reynaert et al., 1997]. Microwave drilling was reported to drill holes (in silicon) with diameters ranging from 1 to 10 mm [Jerby et al., 2002]. The diameters of holes drilled in silicon using ultrasonic vibration assisted drilling (with the ultrasonic workpiece holder) were less than 1 mm [Tsui et al. 2008]. It is desirable to find drilling methods that can produce larger holes and do not cause any HAZ.

Rotary Ultrasonic Machining (RUM) is a nontraditional machining process. It can drill holes with diameters from 3.2 mm (1/8 in) to 28.6 mm (1 1/8 in). It does not cause HAZ. RUM has been reported to drill different materials, as summarized in Table 4.1. However, there is no report in the literature on RUM of silicon.

Table 4.1 Summery of workpiece materials machined by RUM.

Material	Reference
Alumina	[Tyrrell, 1970a; Zhang et al., 2000; Hu et al., 2003; Li et al., 2005a; Zeng et al., 2004; Jiao et al., 2005a,b]
Beryllium oxide	[Tyrrell, 1970a]
Canasite	[Khanna et al., 1995]
Composites	[Tyrrell, 1970a; Li et al., 2005b,c; Li et al., 2007]
Ferrite	[Tyrrell, 1970b]
Glass	[Tyrrell, 1970a; Ya et al., 2002; Treadwell and Pei, 2003]
KDP	[Wang et.al 2008, 2009ab]
Polycrystalline diamond compact	[Li et al., 2004]
Silicon carbide	[Zeng et al., 2005; Churi et al., 2007c]
Silicon nitride	[Pei et al., 1995a]
Stainless steel	[Cong et al., 2009abcd]
Titanium	[Churi et al., 2005; Churi et al., 2006; Churi et al., 2007a,b]
Uranium oxide cermet	[Tyrrell, 1970a]
Zirconia	[Prabhakar, 1992; Pei et al., 1995b; Pei and Ferreira, 1998; Pei and Ferreira, 1999; Pei et al., 1995c]

This paper presents a study on edge chipping in RUM of silicon. Edge chipping is an important parameter to evaluate hole quality. Edge chipping in a machined brittle material workpiece not only compromises geometric accuracy, but also causes possible failure of the component during service [Ng et al., 1996; Chai and Lawn, 2007]. Therefore, it is important to study and reduce/eliminate edge chipping in RUM of silicon.

In this study, two-level three-factor full factorial design was employed to experimentally determine effects of input variables on edge chipping and cutting force. The experimentally determined relation between edge chipping and cutting force was compared with that obtained by finite element analysis. There are six sections in this paper. Following this introduction section, Section 4.2 describes experimental conditions and measurement procedures. Section 4.3 presents and discusses experimental results. Section 4.4 presents the relation between edge

chipping and cutting force obtained by finite element analysis and makes a comparison with the experimentally determined relation. Finally, Section 4.5 draws conclusions.

4.2 Experimental conditions and procedure

4.2.1 Experimental conditions

The drilling experiments were performed on a Sonic-Mill Series 10 RUM machine (Sonic-Mill, Albuquerque, NM, USA). RUM is illustrated in Figure 4.1. The cutting tool was a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrated axially at an ultrasonic frequency and moved along its axial direction towards the workpiece. Coolant was injected to the interface between the tool and workpiece surface to keep the cutting tool and workpiece cool. The RUM experimental set-up is shown in Figure 4.2. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system comprised of an ultrasonic spindle and a power supply. The power supply converted low frequency (60 Hz) electrical supply into high frequency (20 kHz) AC output. This AC output was converted into mechanical vibrations by the piezoelectric transducer in the ultrasonic spindle.

Figure 4.1 Illustration of RUM of silicon.

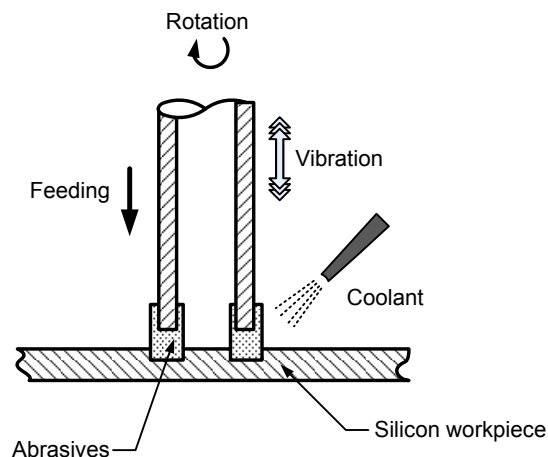
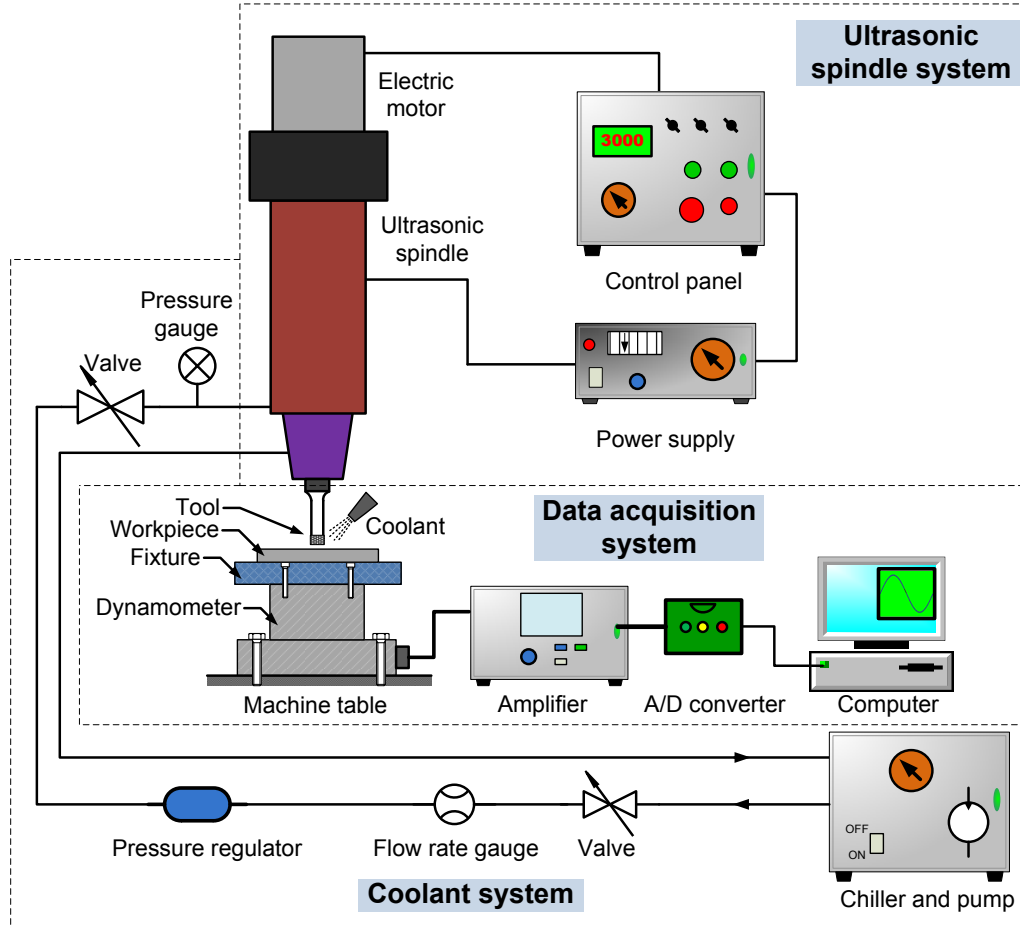


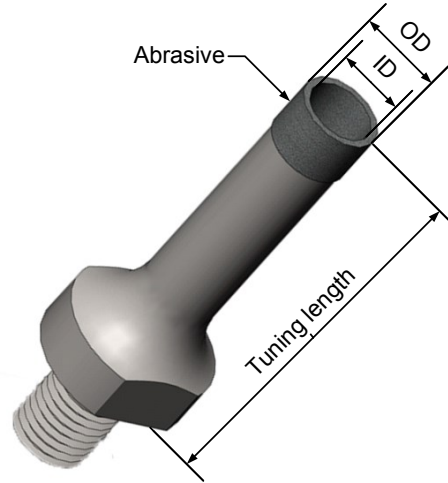
Figure 4.2 Experimental set-up.



The coolant system mainly included a refrigerated recirculator (including chiller, pump, and container), pressure regulator, flow rate gauge, pressure gauge, and valves. A refrigerated recirculator (CFT-75, Neslab Instrument Inc. Portsmouth, NH, US) could generate cold water (15 °C in this study) and pump it to the ultrasonic spindle to keep the ultrasonic spindle cool. The cold water was also injected to the interface between the tool and workpiece.

The metal-bonded diamond tools, as illustrate in Figure 4.3, were provided by NBR Diamond Tool Corp. (LaGrangeville, NY, USA). The outer and inner diameters (OD and ID) of the tool were 9.53 mm and 8.00 mm, respectively, and the tuning length was 45 mm. The size of the diamond abrasives was mesh 140/170 (about 89 – 104 μm).

Figure 4.3 Illustration of RUM tool.

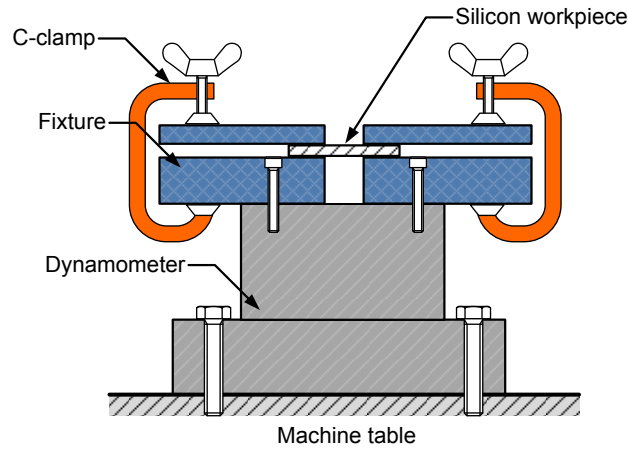


The properties of silicon are shown in Table 4.2. Silicon workpieces were cut from 200 mm silicon wafers with (100) plane as their major surface. The size of silicon workpieces was 20 mm $\times$ 20 mm $\times$ 0.7 mm. The custom designed fixture had two aluminum plates and each of them had a hole with a diameter of 12.7 mm. One of the plates was mounted onto the dynamometer by four screws. The silicon workpiece was put in between these two aluminum plates and the two plates were fixed by two C-clamps, as shown in Figure 4.4.

Table 4.2 Mechanical properties of silicon (SolidWorks software database).

Property	Value
Young's modulus (GPa)	112.4
Poisson's ratio	0.28
Ultimate tensile strength (MPa)	129

Figure 4.4 Fixing of silicon workpiece.



4.2.2 Design of experiments

A 2^3 (two-level, three-factor) full factorial design [Myers et al., 2008] was employed. There were eight unique experimental conditions. Under each condition, two tests were conducted. The total number of tests was 16. Based on the experience from preliminary experiments and due to the limitations of the experimental set-up, the following three input variables were studied:

- Tool rotation speed: rotational speed of the tool;
- Ultrasonic power: percentage of power from ultrasonic power supply, controlling the ultrasonic vibration amplitude;
- Feedrate: feedrate of the tool toward the silicon workpiece.

Table 4.3 lists these variables and their values at the high and low levels.

Table 4.3 High and low levels of input variables.

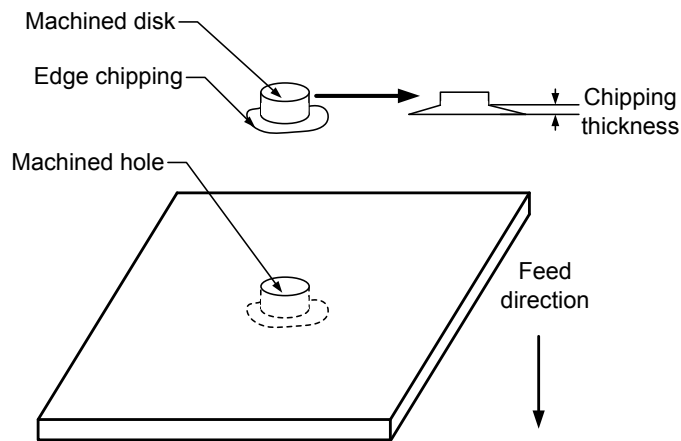
Input variable	Unit	Low level	High level
Tool rotation speed	rpm	2000	4000
Feedrate	mm/s	0.01	0.03
Ultrasonic Power	%	20	50

4.2.3 Measurement procedures

Figure 4.5 illustrates the edge chipping induced in the RUM process. In RUM, the workpiece was machined into two pieces (disk and hole). One piece was the machined part with the desired hole, the other was a disk removed from the workpiece. When the cutting tool nearly drilled through the workpiece, the disk broke off from the workpiece, causing the edge chipping around the hole exit edge. The chipping thickness measured on the machined disk was used to quantify the edge chipping. The chipping thickness measured on the machined disk was used to quantify the edge chipping. Such choice was based on the following reasons:

- (1) the edge chipping on the drilled hole exactly matches the edge chipping on the machined disk;
- (2) it is more convenient to measure the thickness of edge chipping formed on the machined disk.

Figure 4.5 Illustration of edge chipping.



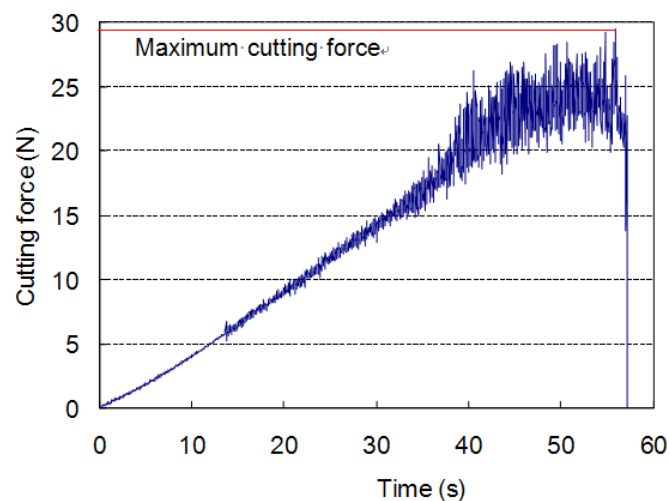
The thickness of the edge chipping was measured by a microscope (Model BX51M Olympus Inc. Tokyo, Japan). The eyepiece of the microscope had a magnification of 10 and the

objective lens had a magnification of 5. The combination of the two gave a total magnification of 50.

A dynamometer (Model 9272, Kistler Inc., Switzerland) was used to measure the cutting force. The electrical signals from the dynamometer were amplified by a charge amplifier (Model 5070, Kistler Inc., Switzerland). The electrical signals from the amplifier were transformed into digital signals by an A/D converter (National instrument Inc, Austin, TX, USA). The digital signals were saved on a computer with the help of a program written in LabView (Version 5.1, National Instruments, Austin, TX, USA). The sampling rate was 20 per second.

The cutting force reported in this paper is the cutting force in the tool axial direction during the RUM experiments. It varied with time and fluctuated within a certain range. Figure 4.6 shows a typical graph of cutting force versus time. The maximum cutting force for each test (as illustrated in Figure 4.6) was used for graphing and analysis in this paper.

Figure 4.6 Typical relationship between cutting force and time



4.3 Experimental results

The test matrix and experimental results are listed in Table 4.4. The software Minitab (version 15, Minitab Inc. State College, PA) was used to analyze the data. The software can perform ANOVA (analysis of variance) to identify significance effects. Geometric representations of significant effects at the significance level of $\alpha = 0.05$ are presented in this paper with discussions.

Table 4.4 Test matrix and experimental results.

Standard Order	Run Order	Tool Rotation Speed	Ultrasonic power	Feedrate	Cutting force (N)	Edge chipping thickness (mm)
1	11	-1	-1	-1	14.0	0.25
2	9	1	-1	-1	8.5	0.21
3	12	-1	1	-1	10.1	0.23
4	13	1	1	-1	7.8	0.19
5	16	-1	-1	-1	13.0	0.25
6	10	1	-1	-1	8.3	0.20
7	15	-1	1	-1	9.8	0.22
8	14	1	1	-1	7.7	0.19
9	8	-1	-1	1	27.8	0.32
10	2	1	-1	1	14.8	0.27
11	4	-1	1	1	21.2	0.30
12	1	1	1	1	14.2	0.26
13	7	-1	-1	1	27.8	0.32
14	3	1	-1	1	15.4	0.28
15	5	-1	1	1	22.4	0.29
16	6	1	1	1	13.9	0.26

4.3.1 Main effects on edge chipping

Table 4.5 shows ANOVA results on edge chipping. It can be seen that main effects of all three input variables (tool rotation speed, ultrasonic power, and feedrate) are significant. These main effects are presented in Figures 4.7-4.9. Edge chipping thickness decreased as tool rotation

speed or ultrasonic power increased, but increased as feedrate increased. According to the test statistic values (as shown in the second column of Table 4.5), the main effect of feedrate was the most significant, followed by tool rotation speed.

Table 4.5 Effects on edge chipping thickness.

Factor	Test statistic (T)	P-value
Constant	267.17	0.000*
A-Tool rotation speed	-21.08	0.000*
B-Ultrasonic Power	-10.90	0.000*
C-Feedrate	36.81	0.000*
AB interaction	1.12	0.294
AC interaction	-12.66	0.949
BC interaction	2.79	0.750
ABC interaction	-0.82	0.568

* indicating a significant effect at the level of $\alpha = 0.05$.

The trends of effects of tool rotation speed and feedrate on edge chipping are consistent with those in RUM of advanced ceramics reported by Jiao et al. (2005) and ceramic matrix composites by Li et al. (2005). The main effect of ultrasonic power was not significant in these two papers probably because the ranges of the ultrasonic power were from 30% to 45% and 35% to 50% in these two papers, respectively, which were much smaller than that used in this paper (from 20% to 50%).

Interaction effect of input variables on edge chipping were not significant at the significance level of $\alpha = 0.05$.

Figure 4.7 Main effect of tool rotation speed on edge chipping.

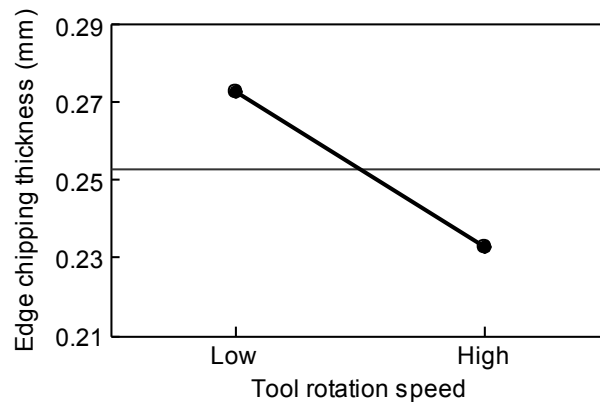


Figure 4.8 Main effect of ultrasonic power on edge chipping.

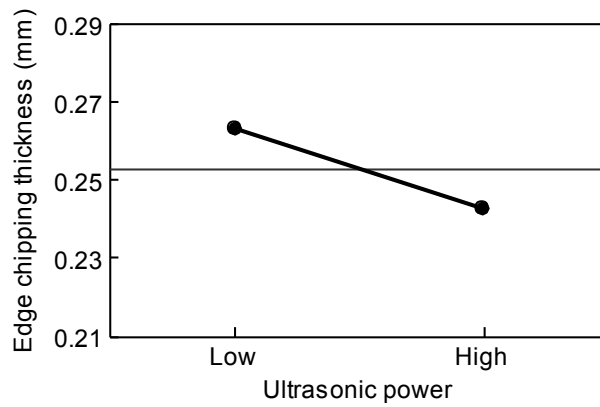
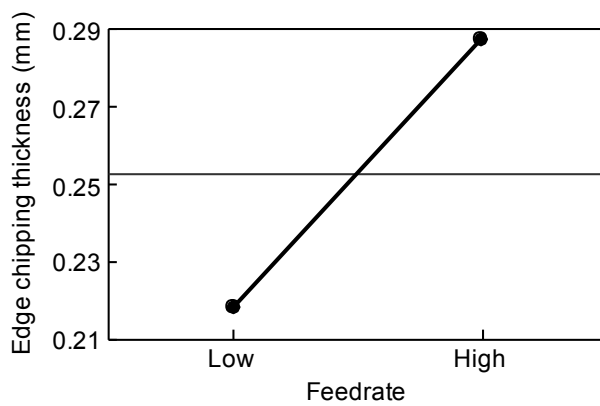


Figure 4.9 Main effect of feedrate on edge chipping.



4.3.2 Main effects on cutting force

According to ANOVA results (Table 4.6), main effects of all three input variables (tools rotation speed, ultrasonic power, and feedrate) on cutting force are significant. They are presented in Figures 4.10-4.12, respectively. It can be seen that cutting force decreased as tool rotation speed and ultrasonic power increased, but decreased as feedrate increased. According to the test statistic values (the second column of Table 4.6), the main effect of feedrate was the most significant, followed by tool rotation speed. These three effects are consistent with those observed for RUM of stainless steel by Cong et al. (2008). The effects of feedrate and tool rotation speed on cutting force are consistent with those for RUM of SiC observed by Churi et al. (2007), and for RUM of alumina by Jiao et al. (2005). The effects of feedrate on cutting force are also consistent with those for RUM of ceramic matrix composites observed by Li et al. (2005). However, the effects of ultrasonic power have a different trend from those reported previously with different workpiece materials. It is possible that the differences in the range of the ultrasonic power used in different experiments caused the different trends.

Table 4.6 Effects on cutting force.

Factor	Test statistic (T)	P-value
Constant	134.82	0.000*
A-Tool rotation speed	-31.59	0.000*
B-Ultrasonic Power	-12.91	0.000*
C-Feedrate	44.58	0.000*
AB	8.96	0.000*
AC	-15.01	0.000*
BC	-3.20	0.013*
ABC	2.32	0.049*

* indicating a significant effect at the level of $\alpha = 0.05$.

Figure 4.10 Main effect of tool rotation speed on cutting force.

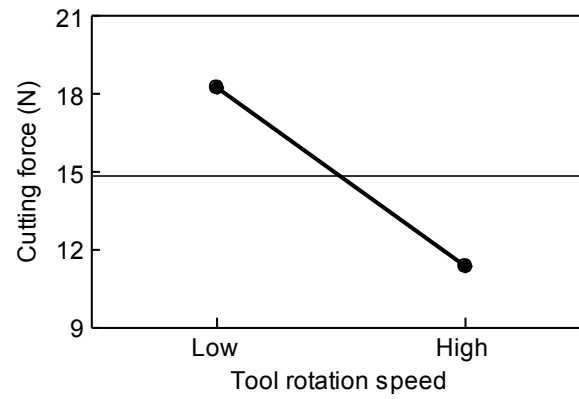


Figure 4.11 Main effect of ultrasonic power on cutting force.

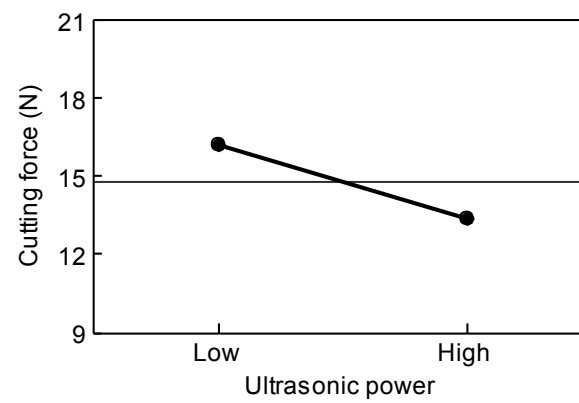
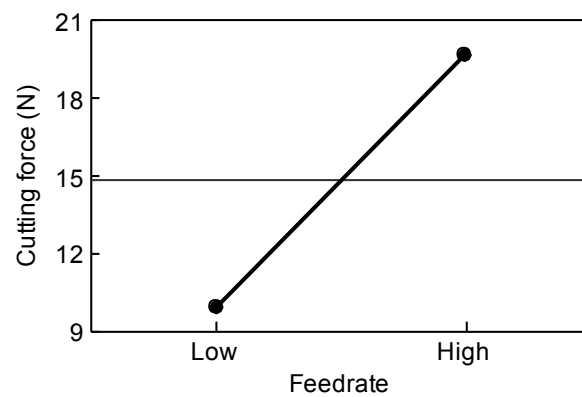


Figure 4.12 Main effect of feedrate on cutting force.



4.3.3 Interaction effects on cutting force

Three two-factor interaction effects can be obtained by this two-level three-factor factorial design. It can be seen from Table 4.6 that all three two-factor interaction effects on cutting force are significant. They are plotted in Figures 4.13-4.15, respectively.

The interaction effects of ultrasonic power and tool rotation speed are shown in Figure 4.13. As ultrasonic power increased, cutting force decreased at both high and low levels of tool rotation speed, but with different slopes. At the low level of tool rotation speed, the absolute value of the slope was larger.

The interaction effects of feedrate and tool rotation speed are shown in Figure 4.14. It can be seen that, as feedrate increased, cutting force increased at both high and low levels of tool rotation speed, but with different slopes. The slope was larger at the low level of tool rotation speed caused a larger slope.

The interaction effects of ultrasonic power and feedrate are shown in Figure 4.15. It can be seen that, as feedrate increased, cutting force increased at both high and low levels of ultrasonic power with different slopes. The slope was larger at the low level of ultrasonic power.

The three-factor interaction effects of tool rotation speed, ultrasonic power, and feedrate, as shown in Figure 4.16, were significant. The combination when the cutting force was the lowest was high tool rotation speed, high ultrasonic power, and low feedrate.

Figure 4.13 Interaction effects between ultrasonic power and tool rotation speed on cutting force.

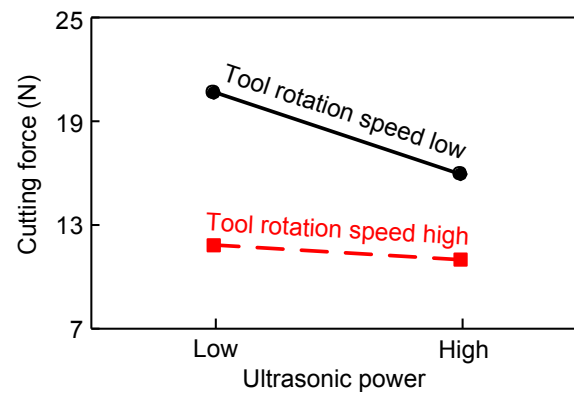


Figure 4.14 Interaction effects between feedrate and tool rotation speed on cutting force.

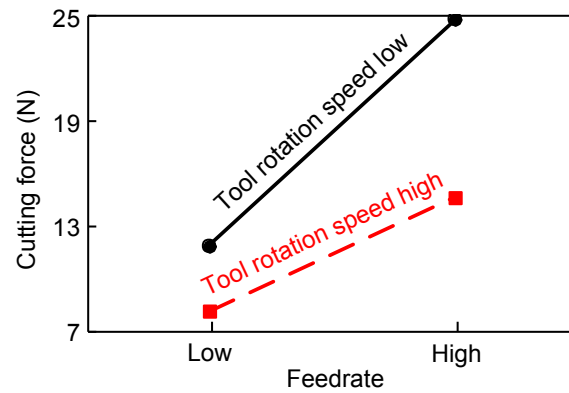


Figure 4.15 Interaction effects between feedrate and ultrasonic power on cutting force.

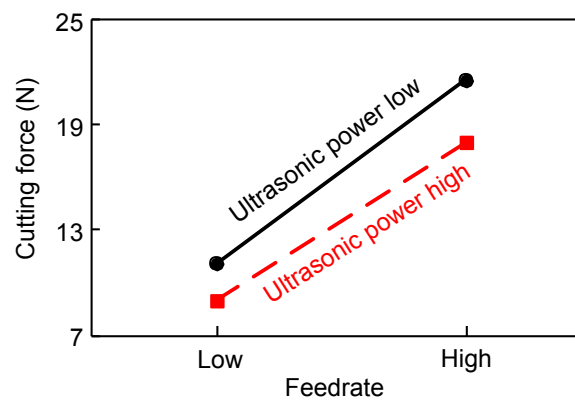
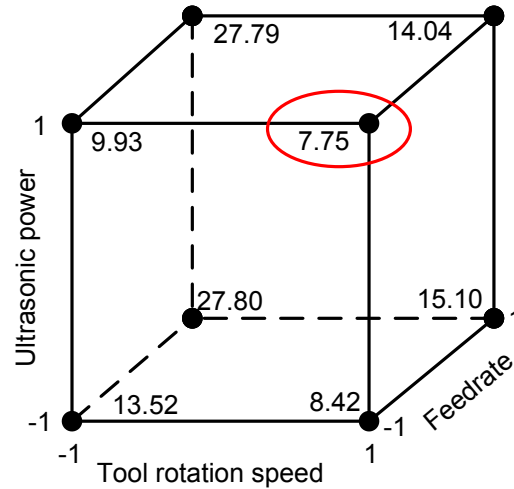


Figure 4.16 Three-factor interaction effects on cutting force.

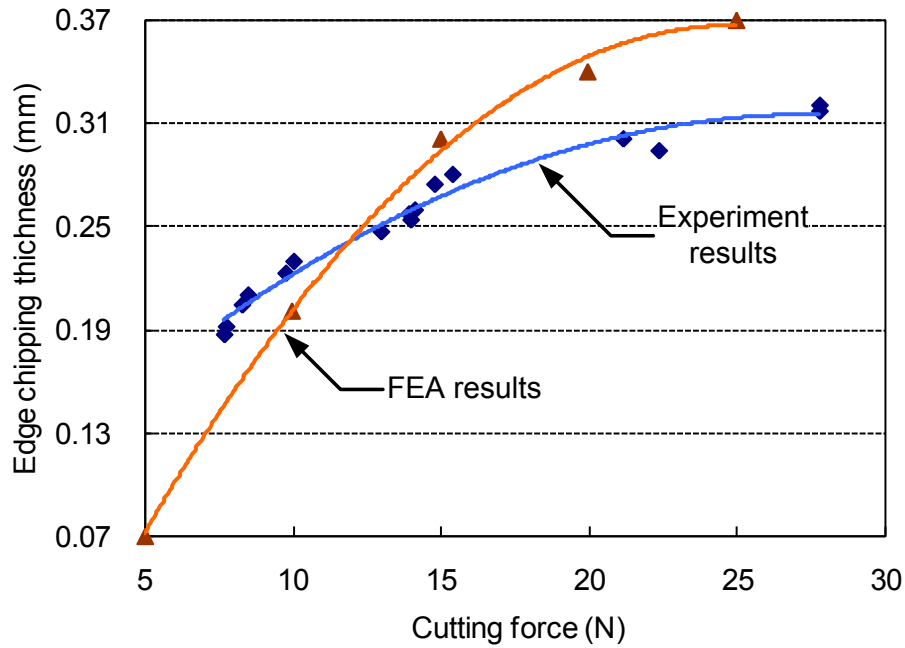


4.3.4 Relationships between cutting force and edge chipping

By comparing Figures 4.7-4.12, it can be seen that, for all three input variables, their main effects of on cutting force had the same trends as their main effects on edge chipping.

In Figure 4.17, the cutting force data (column 6 in Table 4.4) and the edge chipping thickness data (column 7 in Table 4.4) under each test condition are plotted together. It can be seen that larger edge chipping was almost always accompanied by higher cutting force. This correlation indicates that cutting force was an important influencing parameter on edge chipping. In the next section, finite element analysis (FEA) model will be used to predict the relationship between cutting force and edge chipping.

Figure 4.17 Relationships between cutting force and edge chipping.



4.4 FEA simulation on edge chipping

4.4.1 Failure criterion of edge chipping

The FEA model in this study only took into consideration the static stress distribution in the region where edge chipping initiated. It was assumed that edge chipping would initiate when the maximum stress satisfied a failure criterion. Edge chipping thickness was predicted by the FEA model as the vertical distance between the location where edge chipping initiated and the bottom surface of the workpiece.

According to the maximum-normal-stress criterion (also known as Coulomb's criterion) [Beer et al., 2004; Walter and Deborah, 2007], edge chipping was assumed to initiate if $\sigma \geq \sigma_{UTS}$ where σ was the first principle stress obtained from the FEA simulation and σ_{UTS} was the ultimate tensile strength of the workpiece material.

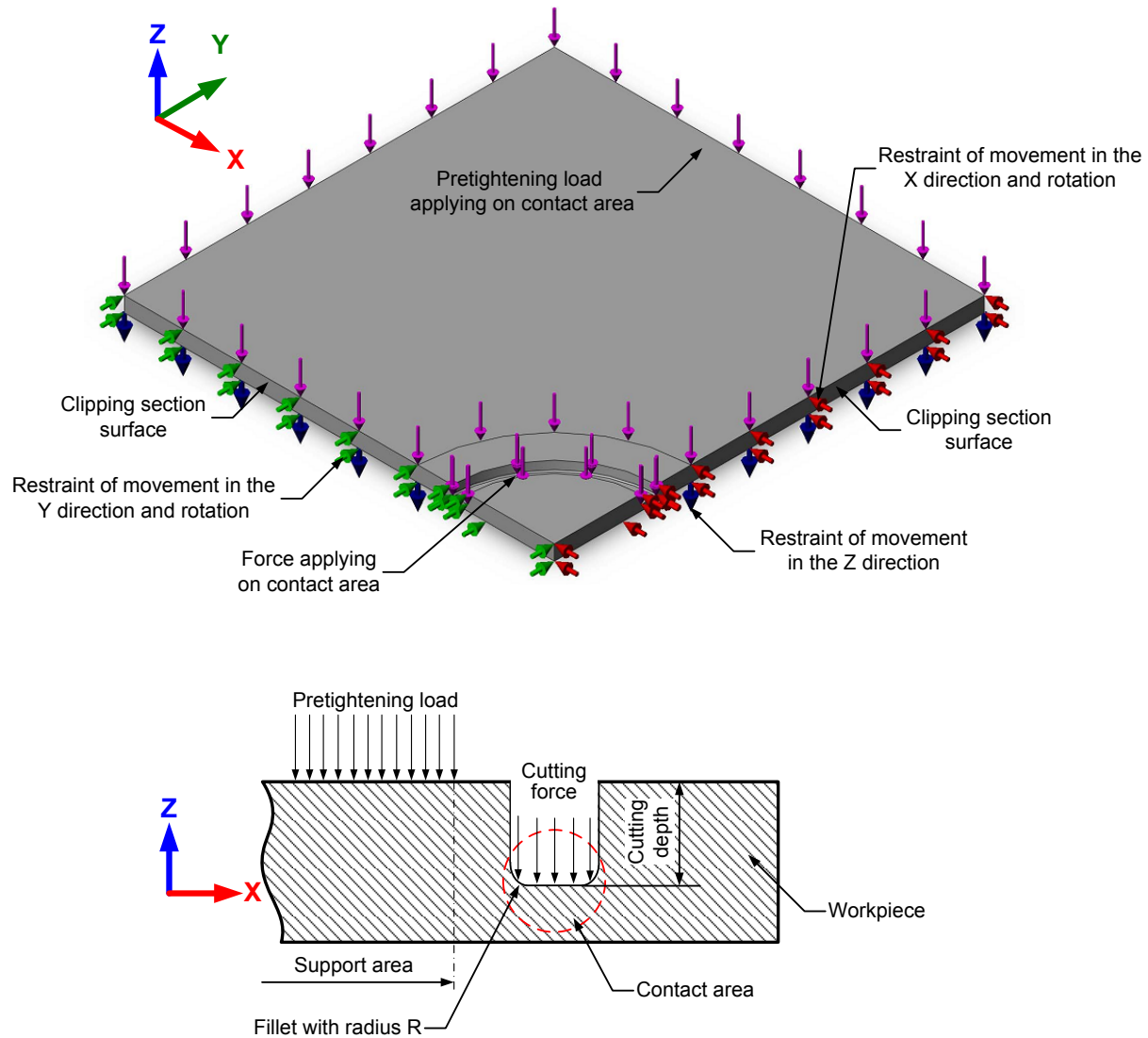
4.4.2 The FEA model

SolidWorks-simulation (SolidWorks Corp., Concord, MA, USA) was used to build a three-dimensional model to simulate (calculate) the workpiece deformation during RUM. Figure 4.18 shows the FEA model. Fine mesh with about 10000 elements was used. The workpiece was modeled as a square plate (40 mm $\times$ 40 mm $\times$ 0.7 mm) with a cylindrical recess with an outer diameter (OD) of 9.5 mm and an inner diameter (ID) of 8.0 mm. The OD and ID of the cylindrical recess were the same as those of the core drill. On any X-Z cross-section (perpendicular to the top surface of the workpiece) through the axis of the core drill, this cylindrical recess became two rectangular recesses. The corner of the rectangular recess in contact with the tool during drilling was modeled as a fillet with a radius (R) of 0.05 mm. The cutting depth was the distance between the top surface of the workpiece and the horizontal machined surface (i.e. the bottom of the rectangular recess), ranging from 0 to 0.7 mm.

The contact area between the tool end surface and the horizontal machined surface in the workpiece consisted of a left fillet region, a middle horizontal contact region, and a right fillet region. The cutting force was applied on the bottom of the rectangular recess.

As illustrated in Figure 4.18, only one quarter of the workpiece was modeled, so two symmetry restraints were applied on the two clipping section surfaces (where clip the workpiece into one quarter size). Sliding in both horizontal directions (the X and Y directions) and rotations were constrained. The fixture was a platform with a center hole of 12.7 mm (0.5 inches) in diameter. The backside of the workpiece in contact with the fixture surface was also constrained from moving in the vertical direction (the Z direction) by roller restraints. Fine mesh with about 10000 elements was used.

Figure 4.18 Finite element analysis model of RUM of silicon.



4.4.3 Simulation Results

Figure 4.17 plots the correlation between cutting force and edge chipping thickness obtained from FEA simulations. It can be seen that edge chipping thickness increases with the increase of cutting force. The predicted trend is consistent with that obtained from experiments.

4.5 Conclusions

This paper presents results of a study on edge chipping in drilling silicon by rotary ultrasonic machining. This study employs an integrated approach that combines designed experiments and FEA simulations. Major conclusions are as following.

- (1) Main effects of three input variables (tool rotation speed, ultrasonic power, and feedrate) on edge chipping were significant. Higher tool rotation speed and ultrasonic power, and lower feedrate led to smaller edge chipping thickness.
- (2) Main effects of three input variables (tool rotation speed, ultrasonic power, and feedrate) on cutting force were significant. Higher tool rotation speed and ultrasonic power, and lower feedrate led to lower cutting force. All two-factor and three-factor interaction effects on cutting force were significant.
- (3) An important influencing parameter on edge chipping was cutting force. Large edge chipping was almost always accompanied by higher cutting force.

Acknowledgments

The work was supported by the National Science Foundation through Award CMMI-0900462. The authors would like to thank Mr. Bruno Renzi at NBR Diamond Tool Corp. for providing the diamond tools, and Dr. Graham Fisher at MEMC Electronic Materials, Inc., for providing the silicon wafers.

References

Asada S, Sano T, Miyamoto I. High-efficiency microdrilling of silicon wafer using excimer laser. In: Proceedings of SPIE - The International Society for Optical Engineering 2000; 4088: 132-135.

Beer FP, Johnston ER, Dewolf JT. Mechanics of Materials. third ed. New York (NY, USA): The McGraw-Hill Company; 2004. [Chapter 7].

Chai H, Lawn BR. Edge chipping of brittle materials: effect of side-wall inclination and loading angle. International Journal of Fracture 2007; 145(4): 159-165.

Chung, CK, Wu MY, Sung YC. Method of Cutting and Machining a Silicon Wafer. US patent: 2007/0287266 A1; 2007.

Churi NJ, Li ZC, Pei ZJ, Treadwell C. Rotary ultrasonic machining of titanium alloy: a feasibility study. In: CD-ROM Proceedings of the International Mechanical Engineering Congress and Exposition 2005.

Churi NJ, Pei ZJ, Treadwell C. Rotary ultrasonic machining of titanium alloy: effects of machining variables. Machining Science and Technology 2006; 10(3): 301-321.

Churi NJ, Pei ZJ, Treadwell C. Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables. International Journal of Precision Technology 2007a; 1(1): 85-96.

Churi NJ, Pei ZJ, Treadwell C. Wheel wear mechanisms in rotary ultrasonic machining of titanium. In: CD-ROM Proceedings of the International Mechanical Engineering Congress and Exposition. 2007b.

Churi NJ, Pei ZJ, Treadwell C, Shorter D. Rotary ultrasonic machining of silicon carbide: designed experiments. International Journal of Manufacturing Technology and Management 2007c; 12(1-3): 284-298.

Cong WL, Pei ZJ, Churi NJ, Wang QG. Rotary ultrasonic machining of stainless steel: design of experiments. Transactions of North American Manufacturing Research Institution /SME 2009a; 37: 261-268.

Cong WL, Pei ZJ, Wang QG. Surface roughness in rotary ultrasonic machining of stainless steel. In: Proceedings of the 2009 Industrial Engineering Research Conference. 2009c.

Cong WL, Pei ZJ, Deines T, Wang QG, Treadwell C. Rotary ultrasonic machining of stainless steels: empirical study of machining variables. International Journal of Manufacturing Research 2010; 5(3): 370-386.

DOE/EIA-0389. Annual energy outlook 2009 with projections to 2030. Available at: [http://www.eia.doe.gov/oiaf/aeo/pdf/0383\(2009\).pdf](http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2009).pdf). 2009.

Flower G. Solar manufacturing: The sun always rises. Surface Mount Technology Magazine 2009; 23(1): 3.

Gartner Inc. Gartner says worldwide silicon wafer revenue reached \$ 12.5 billion in 2007. Available at: <http://www.gartner.com/it/page.jsp?id=691611>. 2008.

Geng N, Fu X, Li HX, Ni XC, Hu XT. Effects of laser parameters in the micromachining of silicon by femtosecond pulse laser. Key Engineering Materials 2007; 339: 136-140.

Hu P, Zhang JM, Jiao Y, Pei ZJ, Treadwell C. Experimental investigation on coolant effects in rotary ultrasonic machining. In: Proceedings of the NSF Workshop on Research Needs in Thermal Aspects of Material Removal Processes. 2003; p. 340-345.

International Energy Agency. Key world energy statistics. Available at: http://www.iea.org/textbase/nppdf/free/2009/key_stats_2009.pdf. 2009.

Jerby E, Dikhtyar V, Aktushev O, Groszlick U. The microwave drill. Science 2002; 298(5593): 578-579.

Jiao Y, Hu P, Pei ZJ, Treadwell C. Rotary ultrasonic machining of ceramics: Design of experiments. International Journal of Manufacturing Technology and Management 2005a; 7(2-4): 192-206.

Jiao Y, Liu WJ, Pei ZJ, Xin XJ, Treadwell C. Study on edge chipping in rotary ultrasonic machining of ceramics: an integration of designed experiments and finite element method analysis. *Journal of Machining Science and Engineering* 2005b; 127(11): 752-758.

Khanna N, Pei ZJ, Ferreira PM. Experimental investigation of rotary ultrasonic grinding of ceramic disks. *Transactions of North American Manufacturing Research Institution /SME* 1995; 23: 67-72

Li ZC, Jiao Y, Deines TW, Pei ZJ, Treadwell C. Experimental study on rotary ultrasonic machining (RUM) of poly crystalline diamond compacts (PDC). In: *CD-ROM Proceedings of the 13th Annual Industrial Engineering Research Conference*. 2004.

Li ZC, Jiao Y, Denies TW, Pei ZJ, Treadwell C. Development of an innovative coolant system for rotary ultrasonic machining. *International Journal of Manufacturing Technology and Management* 2005a; 7(2-4): 318-328.

Li ZC, Jiao Y, Deines TW, Pei ZJ, Treadwell C. Rotary ultrasonic machining of ceramic matrix composites: Feasibility study and designed experiments. *International Journal of Machine Tools and Manufacture* 2005b; 45(12-13): 1402-1411.

Li ZC, Pei ZJ, Zeng WM, Kwon P, Treadwell C. Preliminary experimental study of rotary ultrasonic machining on zirconia toughened alumina. *Transactions of North American Manufacturing Research Institution/SME* 2005c; 33: 89-96.

Li ZC, Cai LW, Pei ZJ, Treadwell C. Edge-chipping reduction in rotary ultrasonic machining of ceramics: finite element analysis and experimental verification. *International Journal of Machine Tools and Manufacture* 2006; 46(12-13): 1649-1477.

Li ZC, Pei ZJ, Sisco T, Micale AC, Treadwell C. Experimental study on rotary ultrasonic machining of graphite/epoxy panel. In: Proceedings of the ASPE Spring Topical Meeting on Vibration Assisted Machining Technology. 2007.

Mayerhofer R, Müllers L, Becker A. Laser micro-processing in solar cell production. In: Proceeding of IEEE 4th World Conference on Photovoltaic Energy Conversion. 2006.

Miyamoto I, Asada S, Sano T, Ohmura E. High speed drilling of thin silicon wafer by UV laser. In: Proceedings of International Congress on Applications of Lasers and Electro-Optics 2001; p. 1612-1619.

Myers RH, Montgomery, DC, Anderson-Cook CM. Response Surface Methodology: Process and Product Optimization Using Designed Experiment. Hoboken (NJ, USA): John Wiley & Sons; 2009.

Ng S, Le D, Tucker S, Zhang G. Control of machining induced edge chipping on glass ceramics, in: Proceedings of the 1996 ASME International Mechanical Engineering Congress and Exposition, Manufacturing Engineering Division 1996; MED(4): 229-236.

Quirk M, Serda J. Semiconductor Manufacturing Technology. Second ed. Columbus (OH, USA): Pearson Education International; 2001. p. 67-90. [Chapter 4].

Oxlade C. Fueling the Future Solar Energy. Chicago (IL, USA): Heinemann Library Inc; 2008.

Schropp REI, Zeman M. Amorphous and Microcrystalline Silicon Solar Cells: Modeling, Materials, and Device Technology. New York (NY, USA): Springer Press Inc.; 1998.

Pei ZJ, Ferreira PM, Haselkorn M. Plastic flow in rotary ultrasonic machining of ceramics. Journal of Materials Processing Technology 1995a; 48(1-4): 771-777.

Pei ZJ, Prabhakar D, Ferreira PM, Haselkorn M. A mechanistic approach to the prediction of material removal rates in rotary ultrasonic machining. *Journal of Engineering for Industry* 1995b; 117(2): 142-151.

Pei ZJ. Rotary ultrasonic machining of ceramics: characterization and extensions. Ph.D. Dissertation, University of Illinois at Urbana-Champaign; 1995c.

Pei ZJ, Ferreira PM, Kapoor SG, Haselkorn M. Rotary ultrasonic machining for face milling of ceramics. *International Journal of Machine Tools and Manufacture* 1995d; 35(7): 1033-1046.

Pei ZJ, Ferreira PM. Modeling of ductile mode material removal in rotary ultrasonic machining. *International Journal of Machine Tools and Manufacture* 1998; 38(10-11): 1399-1418.

Pei ZJ, Ferreira PM. An experimental investigation of rotary ultrasonic face milling. *International Journal of Machine Tools and Manufacture* 1999; 39(8): 1327-1344.

Prabhakar D. Machining advanced ceramic materials using rotary ultrasonic machining process, M.S. Thesis, University of Illinois at Urbana-Champaign; 1992.

Reynaerts, D, Heeren PH, Brussel HV, “Microstructuring of silicon by electro-discharge machining (EDM)- part I: theory”, *Sensors and Actuators A: Physical* 1997, 60(1-3): 212-218.

SolidWorks software database, Concord, Massachusetts, USA.

Stolber K, Kremser B, Friedel S, Atsuta Y. Systematic optimization of process parameters in laser drilling of 200 μm photovoltaic silicon wafers using new kind of nanosecond IR lasers. *Journal of Laser Micro Nanoengineering* 2009; 4(3): 231-233.

Treadwell C, Pei ZJ. Machining ceramics with rotary ultrasonic machining. *Ceramic Industry* 2003; (June): 39-42.

- Tyrell WR. Rotary ultrasonic machining. SME Technical Paper 1970a; MR 70516.
- Tyrrell WR. New method for machining hard and brittle materials. SAMPE Quarterly 1970b; 1(2): 55-59.
- Tsui CY, Lu MC, Wu CC, Huang CF. Drilling of microholes on silicon wafer with ultrasonic workpiece holder. In: Proceeding of ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. 2008.
- Uno, Y, Okada A, Nakanishi H, Okamoto Y. Fundamental study on electrical discharge machining of single crystalline silicon. Journal of the Japan Society for Precision Engineering 1997a; 63(10): 1459-1463.
- Uno Y, Okada A, Okamoto Y. High efficiency penetration boring of single crystalline silicon ingot by EDM. Journal of the Japan Society for Precision Engineering 1997b; 63(12): 1725-1729.
- Walter DP, Dehorah FP. Peterson's Stress Concentration Factors. New York (NY, USA): Wiley; 2007. [Chapter 1].
- Wang QG, Pei ZJ, Gao H, Churi N, Kang RK. Rotary ultrasonic machining of potassium dihydrogen phosphate (KDP) crystal: an experimental investigation. International Journal of Mechatronics and Manufacturing Systems 2009a; 2(4): 414-426.
- Wang QG, Cong WL, Pei ZJ, Gao H, Kang RK. Rotary ultrasonic machining of potassium dihydrogen phosphate (KDP) crystal: an experimental investigation on surface roughness. Journal of Manufacturing Processes 2009b; 11: 66-73.
- Ya G, Qin HW, Yang SC, Xu YW. Analysis of the rotary ultrasonic machining mechanism. Journal of Materials Processing Technology 2002; 129(1-3): 182-185.

Yokotani A, Mukumoto T, Kanamitsu Y, Fukumoto H, Kurosawa K. Time-resolving image analysis drilling of thin silicon substrates with femtosecond laser ablation. Japanese Journal of Applied Physics 2005; 44(11): 7998-8003.

Zeng WM, Li ZC, Pei ZJ, Treadwell C. Experimental investigation into rotary ultrasonic machining of alumina. In: Proceedings of International Mechanical Engineering Congress and Exposition. 2004. p. 207-211.

Zeng WM, Li ZC, Pei ZJ, Treadwell C. Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics. International Journal of Machine Tools and Manufacture 2005; 45(12-13): 1468-1473.

Zhang QH, Wu CL, Sun JL, Jia ZX. Mechanism of material removal in ultrasonic drilling of engineering ceramics. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2000; 214(9): 805-810.

Chapter 5 - Aerospace Stainless Steel - Feasibility Study

Paper title:

Rotary ultrasonic machining of stainless steels: empirical study of machining variables

Published in:

International Journal of Manufacturing Research (2010), Vol. 5, No. 3, pp. 370-386

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Deines, T.W.¹, Wang, Q.G.², and Treadwell, C.³

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
2. Key Laboratory of the Ministry of Education for Precision and Non-traditional Machining Technology, Dalian University of Technology, Dalian, Liaoning, China
3. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Stainless steels have a variety of engineering applications and have been machined using many processes. The composite/steel stacks are used increasingly in new generations of industry aircraft, presenting new challenges in drilling holes in these stacks. It has been reported that rotary ultrasonic machining (RUM) could drill composite materials effectively. The feasibility to use RUM to drill stainless steel was also reported. However, there is no report on systematic study on effects of different machining variables in RUM of stainless steel. This paper presents an experimental study on RUM of stainless steels. Cutting force, torque, and surface roughness in RUM of stainless steels have been investigated using different machining variables (including spindle speed, feedrate, and ultrasonic power).

Keywords: Cutting force, Drilling, Rotary ultrasonic machining, Stainless steel, Surface roughness, Torque

5.1 Introduction

Stainless Steels are widely utilized in aerospace, chemical, and medical industries (Liu et al, 2006; Dolinsek, 2003; Urmann, 2008). Characteristics of stainless steels, such as high ductility, poor thermal conductivity, and severe strain hardening, can lead to high temperature and cutting force during machining. As a result, efficiency and tool life are low when drilling stainless steels in many cases of production (Zhong et al., 2004; Jing et al., 2005; Liu et al, 2006; Dolinsek, 2003; Kosmol et al., 1999). To improve twist drilling, a coating of TiN, TiAlN or TiCN has been used and the point and helix angles optimized (Jing et al. 2005, Li et al. 2006a, Liu et al. 2006, Chen et al. 2006, Chen et al. 2007, Deng et al. 1993).

Composite/titanium or composite/steel stacks are used increasingly in newer generations of aircraft. This has resulted in greater challenges to twist drilling. Twist drills wear quickly when drilling composite materials and they often produce burrs at both entrance and exits side of the holes in stainless steel. Frequently, subsequent processes are needed to remove these burrs.

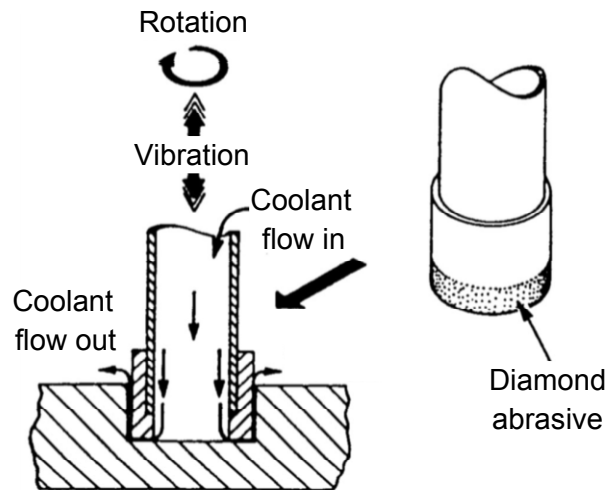
It has been shown that rotary ultrasonic machining (RUM) can effectively drill composite materials (Li et al., 2005b) and titanium (Churi et al., 2005; Churi et al., 2006; Churi et al., 2007a,b). These results indicate that RUM can be a better alternative to drill Composite/Ti or CMC/steel stacks. The feasibility to use RUM to drill stainless steel was shown (Cong et al., 2009a,b). This paper reports an empirical study of machining variables in RUM of stainless steel.

Figure 5.1 illustrates the RUM process. The cutting tool is a core drill made of metal-bonded diamond abrasives. When machining, the rotating tool vibrates at ultrasonic frequencies and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf, preventing the tool from jamming and overheating. Since RUM was invented in 1960's (Legge, 1964), it has been primarily used to machine brittle materials including alumina (Tyrrell, 1970a; Zhang et al., 2000; Hu et al., 2003; Li et al., 2005a; Zeng et al., 2004; Jiao et al., 2005a,b), beryllium oxide (Tyrrell, 1970a), canasite (Khanna et al., 1995), composites (Tyrrell, 1970a; Li et al., 2005b,c; Li et al., 2007), glass (Tyrrell, 1970a; Ya et al., 2002; Treadwell and Pei, 2003), polycrystalline diamond compact (Li et al., 2004), silicon carbide (Zeng et al., 2005; Churi et al., 2007c), silicon nitride (Zeng et al., 2005; Churi et al., 2007c), uranium oxide cermet (Tyrrell, 1970a), and zirconia (Prabhakar, 1992; Pei et al., 1995b; Pei and Ferreira, 1998; Pei and Ferreira, 1999; Pei et al., 1995c).

This paper reports experimental results on effects of spindle speed, feedrate, and ultrasonic power on cutting force, torque, and surface roughness in RUM of stainless steels. The

remainder of this paper is organized as follows. The experimental conditions and procedure are described next. Then, experimental results are presented and discussed. The last section contains conclusions.

Figure 5.1 Illustration of rotary ultrasonic machining.



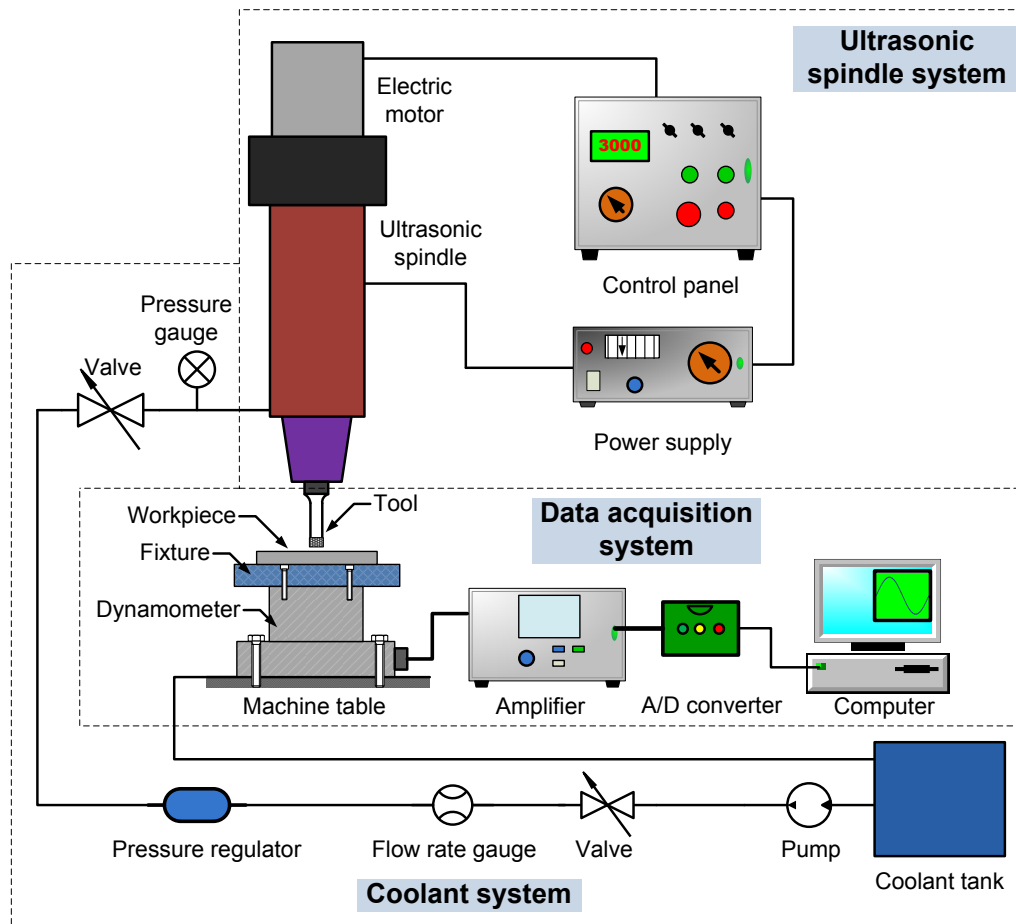
5.2 Experimental conditions and procedure

5.2.1 Experimental conditions

Machining experiments were performed on a Sonic-Mill Series 10 RUM machine (Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is shown in Figure 5.2. It is mainly consists of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system comprises of an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converts 60 Hz electrical supply to high frequency (20 kHz) AC output. This is fed to the piezoelectric transducer located in the ultrasonic spindle. The ultrasonic transducer converts electrical input into mechanical vibrations. The motor attached atop the

ultrasonic spindle supplies the rotational motion of the tool and different speeds can be obtained by adjusting the motor speed controller.

Figure 5.2 Experimental set-up.



A metal-bonded diamond core drill (NBR Diamond tool Corp., LaGrangeville, NY, USA) was used to drill the stainless steels workpieces. The outer and inner diameters of drill were 9.5 mm and 7.8 mm, respectively. The mesh size of diamond abrasives was 80/100. The metal-bonded diamond tool had two slots at the end. Water-soluble Quakercool 6010 cutting fluid (Murdock Industrial Supply Co., Wichita, KS, USA) was used as coolant and diluted with water

at a ratio of 1 to 14. The workpiece material was 15-5 stainless steels. The size of workpieces was $150 \times 125 \times 12.7$ mm.

Based on the experience from preliminary experiments and due to the limitations of the experimental set-up, the experiments were focused on the study of the following three machining variables:

- Spindle speed: rotational speed of core drill
- Feedrate: feedrate of core drill
- Ultrasonic power: percentage of power from ultrasonic power supply, which controls the ultrasonic vibration amplitude

The values of these variables used in the experiments are shown in Tables 5.1-5.3.

Table 5.1 Experiment results for effects of spindle speed.

Spindle speed (rpm)	Cutting force (N)	Torque (N·m)	Surface roughness (μm)	
			Entrance	Exit
1500	518	23.89	0.18	0.49
2000	497	17.38	0.36	0.50
3000	476	15.64	0.38	0.53
4000	466	14.34	0.40	0.54
5000	440	12.60	0.45	0.60

(Feedrate = 0.02 mm/s, ultrasonic power = 30%)

Table 5.2 Experiment results for effects of feedrate.

Feedrate (mm/s)	Cutting force (N)	Torque (N·m)	Surface roughness (μm)	
			Entrance	Exit
0.01	362	11.29	0.32	0.46
0.015	398	13.47	0.33	0.51
0.02	466	14.34	0.40	0.53
0.03	595	14.77	0.42	0.58
0.04	621	17.38	0.46	0.62

(Spindle speed = 4000 rpm, ultrasonic power = 30%)

Table 5.3 Experiment results for effects of ultrasonic power.

Ultrasonic Power (%)	Cutting force (N)	Torque (N·m)	Surface roughness (μm)	
			Entrance	Exit
20	279	8.69	0.58	0.63
25	388	13.03	0.60	0.69
30	466	14.34	0.42	0.54
35	414	15.20	0.57	0.66
40	424	16.07	0.56	0.66

(Spindle speed = 4000 rpm, feedrate = 0.02 mm/s)

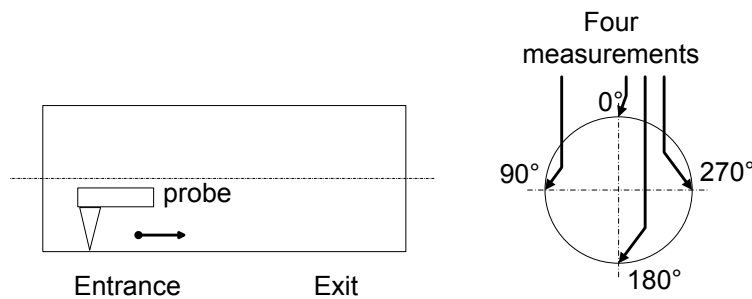
5.2.2 Measurement procedure

Cutting force and torque were measured by Kistler 9297 piezoelectric dynamometer (Kistler Instrument Corp, Amherst, NY, USA). The workpiece was clamped by a fixture amounted on top of the dynamometer. The electrical signals from the dynamometer were transformed into digital signals by an A/D converter. Then the digital signals to measure the cutting force and torque were saved on a computer with the help of Lab-VIEW (Version 5.1, National Instruments, Austin, TX, USA). The sampling frequency to obtain the cutting force and torque signals was 40 Hz. The cutting force and torque reported in this paper are the maximum cutting force and torque for each test. They are of the major concern because they determine the maximum stress in the workpiece, the maximum deformation of the machine, and the damage to the drill.

Since RUM is a core drilling process, a hole and a rod will be produced after each test. Surface roughness was measured on the cylindrical surfaces of machined holes along the feed direction. A surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan) was used with the tested range being set as 4 mm and the cut-off length was set as 0.8 mm. The surface roughness in this study was characterized by Ra, average surface roughness. As shown in Figure 5.3, roughness was measured at two locations along the axial direction of the hole:

entrance and exit. At each location, four measurements were performed with 90 degree between two adjacent measurements. Each measurement was repeated twice. Therefore, for each location, there were eight values of Ra. The average of these eight Ra values was reported for each location.

Figure 5.3 Measurement of surface roughness.



5.3 Results and discussion

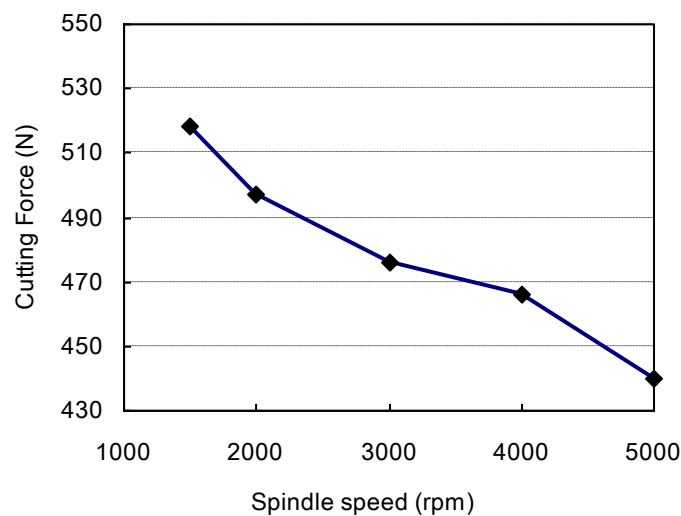
5.3.1 Effects on cutting force

5.3.1.1 Effects of spindle speed

The relationship between cutting force and spindle speed is shown in Figure 5.4. It can be seen that cutting force decreases as spindle speed increases. This result is consistent with those reported for RUM of alumina by Jiao et al. (2005), for RUM of silicon carbide by Churi et al. (2007c), and for RUM of titanium by Churi et al. (2006). However, it is interesting to notice that these results are different from that reported for RUM of ceramic matrix composites (CMC) by Li et al. (2005b). For RUM of CMC, the cutting force increased with the increase of spindle speed. Therefore, it can be said that the effects of spindle speed on cutting force vary for different workpiece materials.

Cutting force in RUM of stainless steel (as well as titanium, alumina, and silicon carbide) will be determined by the interaction force between an average diamond grain on the drill end surface and the workpiece material. This interaction force is affected by the penetration depth of the diamond grain into the workpiece material. As spindle speed increases, the penetration depth of the diamond grain into the workpiece material will decrease (since the feedrate is kept the same). This will reduce the interaction force between the diamond grain and the workpiece material, hence reducing the cutting force.

Figure 5.4 Effects of spindle speed on cutting force.



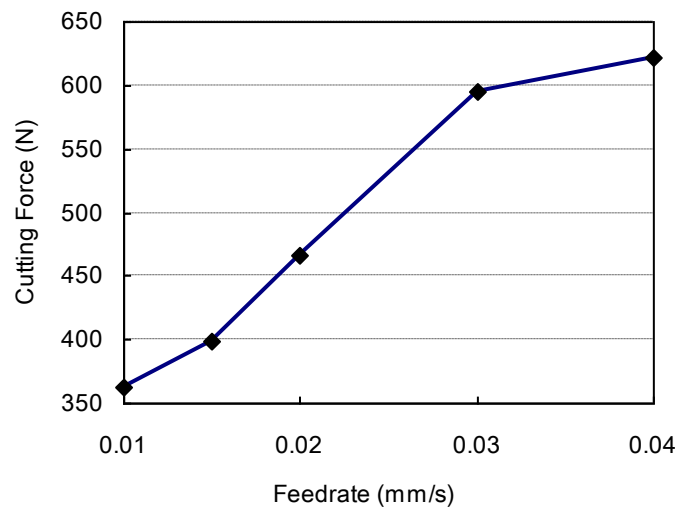
5.3.1.2 Effects of feedrate

Feedrate has significant effects on cutting force, as shown in Figure 5.5. Cutting force increases significantly as feedrate increases. This result is consistent with observations reported for RUM of alumina by Jiao et al. (2005a), for RUM of ceramic matrix composites by Li et al.

(2005b), for RUM on silicon carbide by Churi et al. (2007c), and for RUM of titanium by Churi et al. (2006).

As feedrate increases, the penetration depth of the diamond grain into the workpiece material will increase. This will increase the interaction force between the diamond grain and the workpiece material, hence increasing the cutting force.

Figure 5.5 Effects of feedrate on cutting force.



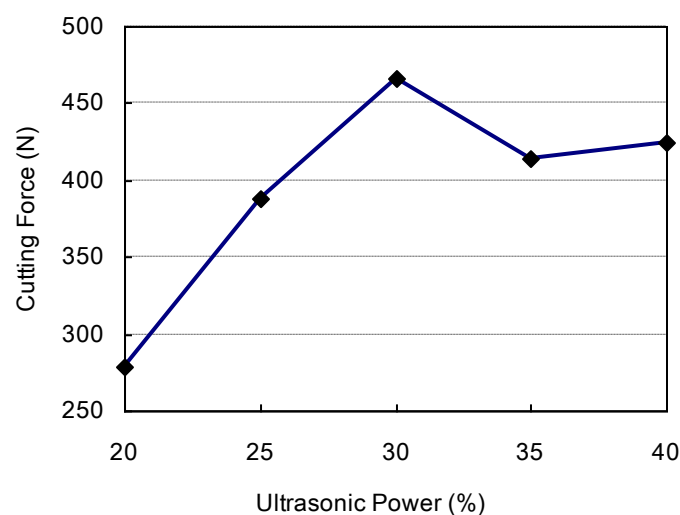
5.3.1.3 Effects of ultrasonic power

The relationship between ultrasonic power and cutting force is shown in Figure 5.6. Cutting force increases as ultrasonic power increases from 20% to 30% and from 35% to 40%, but it decreases as ultrasonic power increases from 30% to 35%. This finding is different from that reported for RUM of titanium by Churi et al. (2006). It is noted that Churi et al. used a different range of ultrasonic power (30% to 60 %). This result is also different from those previously reported for RUM of alumina by Jiao et al. (2005a) and for RUM of ceramic matrix composites by Li et al. (2005b). Jiao et al. found no significant effects of ultrasonic power on

cutting force when RUM of alumina. Li et al. reported that cutting force increased as the ultrasonic power increased for RUM of ceramic matrix composites. Please note that both Jiao et al. and Li et al. used much smaller ranges of ultrasonic power (30% to 45% and 35% to 50%, respectively) because they both used the two-level factorial design. One of the criteria to use the two-level factorial design is that the range of any factor has to be small enough to ensure that the response within the range is approximately linear.

Ultrasonic power determines the vibration amplitude. As ultrasonic power increases, the vibration amplitude will increase (Cong et al., 2009c). This will increase the penetration depth of diamond grain into the workpiece material, increasing the interaction force between the diamond grain and the workpiece material. At the same time, at higher vibration amplitude, the contact time between diamond grain and workpiece material will become shorter. Cutting force will be affected by both the interaction force between the diamond grain and the workpiece material and the contact time between diamond grain and workpiece material.

Figure 5.6 Effects of ultrasonic power on cutting force.

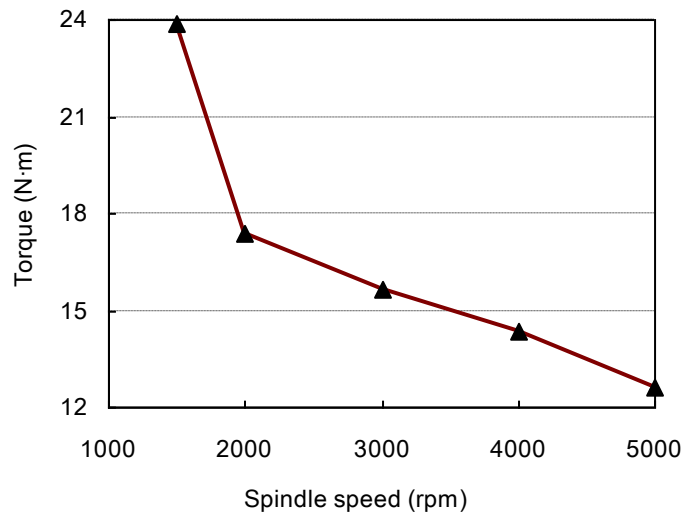


5.3.2 Effects on torque

5.3.2.1 Effects of spindle speed

Figure 5.7 shows the change of torque as feedrate increases. It can be seen that torque decreases with the increase in spindle speed. The torque decreases rapidly when the spindle speed increases from 1500 rpm to 2000 rpm, then decreases nearly linearly at a lower rate when spindle speed increases from 2000 rpm to 5000 rpm. The trends of cutting force and torque as spindle speed increases are the same. No reports have been available in the literature about effects on torque in RUM.

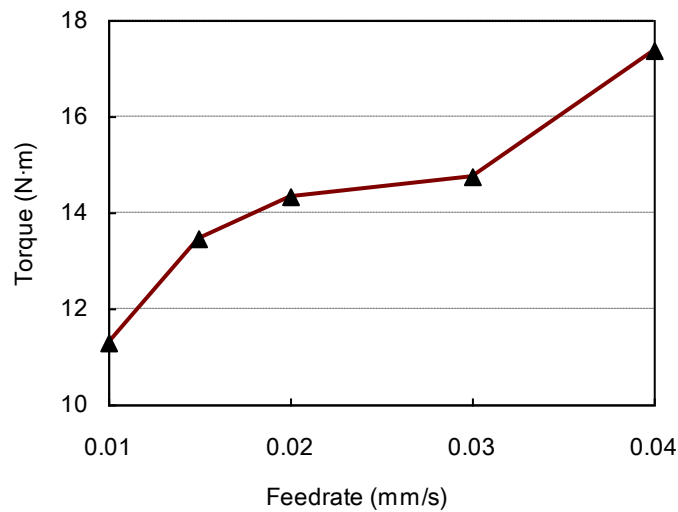
Figure 5.7 Effects of spindle speed on torque.



5.3.2.2 Effects of feedrate

As shown in Figure 5.8, when the feedrate increases, torque increases. This trend is similar to that of cutting force.

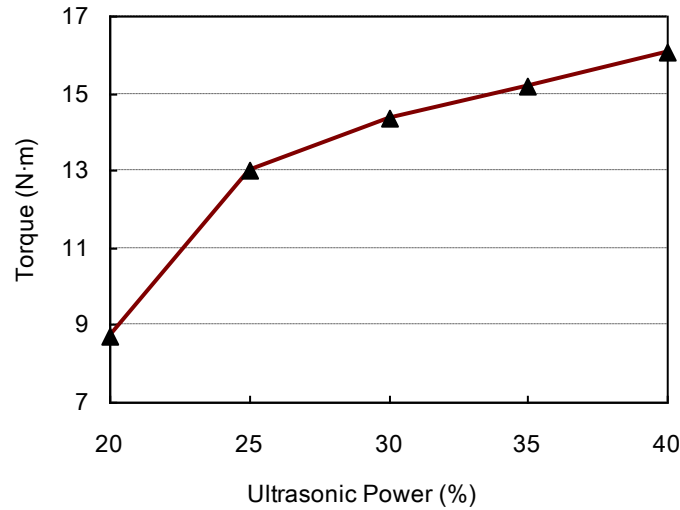
Figure 5.8 Effects of feedrate on torque.



5.3.2.3 Effects of ultrasonic power

Effects of ultrasonic power on torque are depicted in Figure 5.9. The torque increases rapidly initially when ultrasonic power increases from 20% to 25%, and then increases almost linearly at a lower rate when ultrasonic power increases from 25% to 40%. Again, cutting force and torque have a similar trend as ultrasonic power increases.

Figure 5.9 Effects of ultrasonic power on torque.



5.3.3 Effects on surface roughness

5.3.3.1 Effects of spindle speed

Figures 5.10 and 5.11 show the change of surface roughness with spindle speed. At both entrance and exit locations, surface roughness increases with the increase of spindle speed. It also can be observed that the surface roughness at the entrance location increases rapidly when spindle speed increases from 1500 rpm to 2000 rpm, and then increases at a lower rate when spindle speed increases from 2000 rpm to 5000 rpm. But the surface roughness at the exit location increases slowly when the spindle speed increases from 1500 rpm to 4000 rpm, and increases rapidly when the spindle speed increases from 4000 rpm to 5000 rpm. These findings are different from those reported for RUM of alumina by Jiao et al. (2005a), for RUM of silicon carbide by Churi et al. (2007c), and for RUM of titanium by Churi et al. (2006). Both Jiao et al. and Churi et al. reported that surface roughness decreased with the increase of spindle speed. The inconsistencies could be caused by the differences in experimental conditions (for example, the

ranges of ultrasonic power) and in workpiece materials. Further investigations will be conducted to seek for the explanations for such inconsistencies.

Figure 5.10 Effects of spindle speed on surface roughness measured at the entrance location.

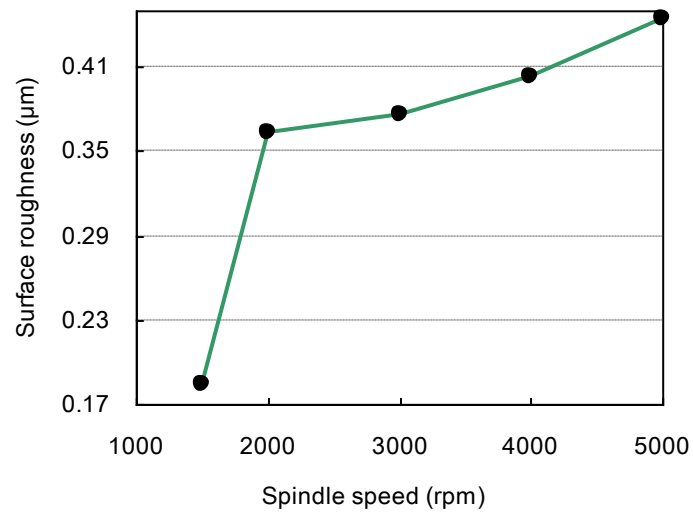


Figure 5.11 Effects of spindle speed on surface roughness measured at the exit location.

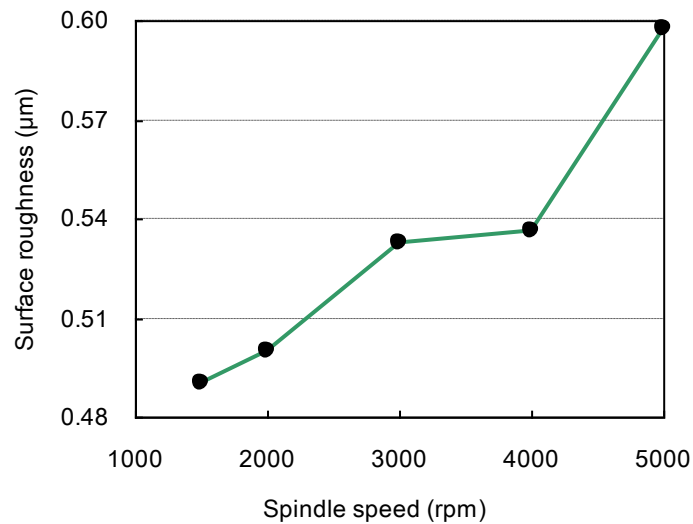


Figure 5.12 Effects of feedrate on surface roughness measured at the entrance location.

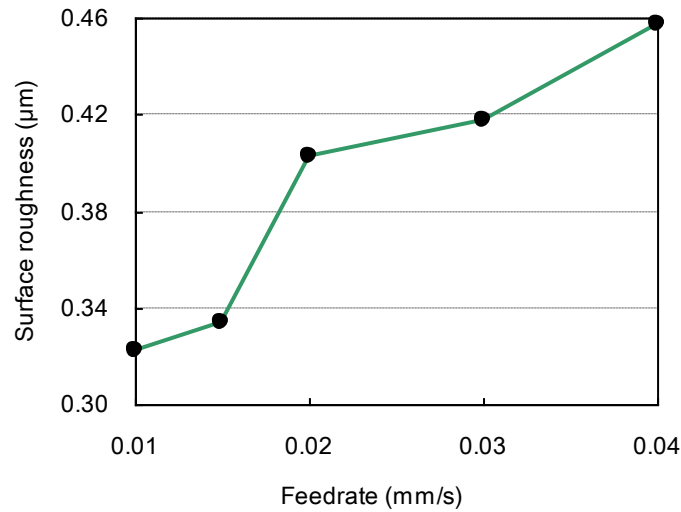
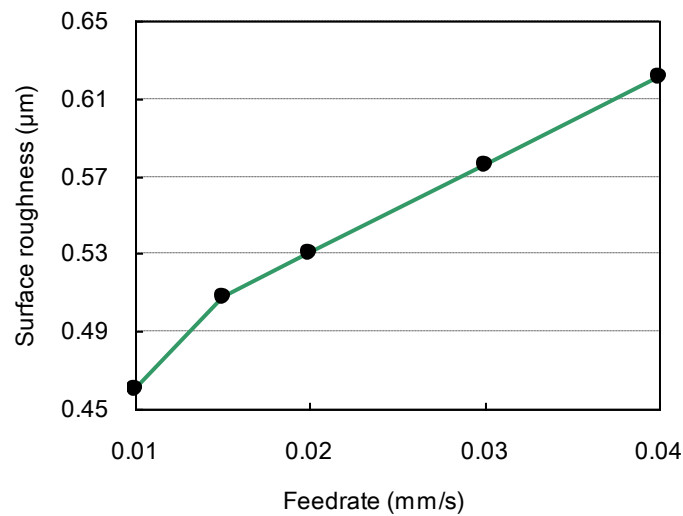


Figure 5.13 Effects of feedrate on surface roughness measured at the exit location.



5.3.3.2 Effects of feedrate

Figures 5.12 and 5.13 show the changes of surface roughness as feedrate increases at the entrance and exit locations, respectively. It can be seen that surface roughness increases as feedrate increases. This result is consistent with those reported for RUM of alumina by Jiao et al.

(2005a), for RUM of silicon carbide by Churi et al. (2007c), and for RUM of titanium by Churi et al., (2006). They stated that surface roughness increased with the increase of feedrate.

5.3.3.3 Effects of ultrasonic power

Figures 5.14 and 5.15 show the changes of surface roughness as ultrasonic power increases at the entrance and exit locations, respectively. It can be seen that, at both entrance and exit locations, surface roughness has the lowest value when ultrasonic power is 30%. This result is different from those reported for RUM of alumina by Jiao et al. (2005a), for RUM of silicon carbide by Churi et al. (2007c), and for RUM of titanium by Churi et al., (2006). They stated that surface roughness increased with the increase of ultrasonic power. Further investigations will be conducted to seek for the explanations for such inconsistencies.

Figure 5.14 Effects of ultrasonic power on surface roughness measured at the entrance location.

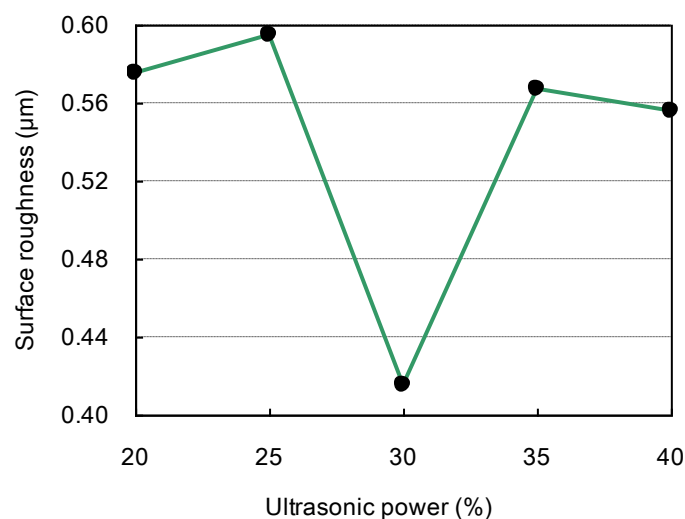
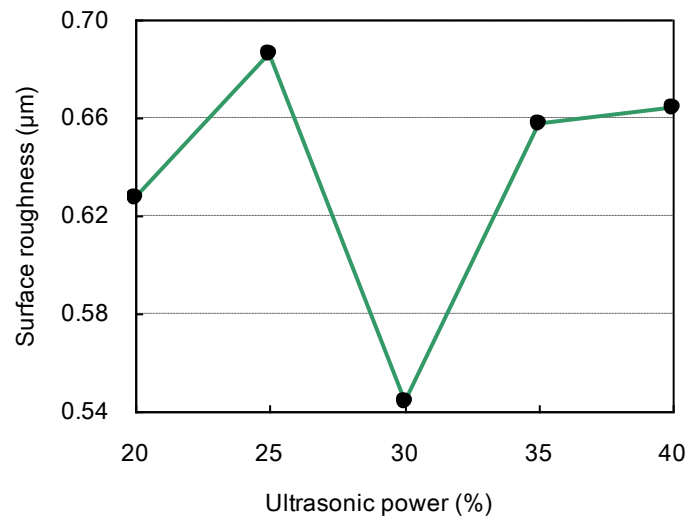


Figure 5.15 Effects of ultrasonic power on surface roughness measured at the exit location.



5.4 Conclusions

In this paper, effects of three machining variables (spindle speed, feedrate, and ultrasonic power) on three output variables (cutting force, torque, and surface roughness) while rotary ultrasonic machining of stainless steels are studied. The following conclusions can be drawn from the study:

- (a) Cutting force decreases as spindle speed increases and as feedrate or ultrasonic power decreases.
- (b) Torque decreases as spindle speed increases and as feedrate or ultrasonic power decreases.
- (c) Surface roughness increases as spindle speed or feedrate increases. Surface roughness is lowest when ultrasonic power is 30%.
- (d) Surface roughness at the entrance location is almost always lower than that at the exit location. This is reported for the first time in the literature. There have been no reports in the literature on surface roughness on both entrance and exit location of holes drilled by RUM. However, similar trends were observed when RUM of titanium and KDP crystal in

the authors' group. Hypotheses have been developed to explain this observed trend and experiments have been conducted to test these hypotheses. Results will be published elsewhere [Cong et al., 2009 d].

Acknowledgments

The work was supported in part by the National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to Mr. Bruno Renzi at N.B.R. Diamond tool Corp. for supplying the diamond core drill.

References

- Chao, C.L., Chou, W.C., Chao, C.W. and Chen, C.C. (2007) 'Material removal mechanisms involved in rotary ultrasonic machining of brittle materials', *Key Engineering Materials*, Vol. 329, pp.391-396.
- Chen, M., Liu, G., Jing, L.L., Hu, Z.G., Zhu, X.F., Li, Z.W. and Xu, H. (2006) 'The development of special drills for high-efficient drilling austenitic stainless steel part II: coating selection and experiment research', *Key Engineering Materials*, Vol. 315-316, pp.200-204.
- Chen, M., Liu, G. and Zhang, X.H. (2007) 'Optimization studies on hole-making tools for high-performance cutting austenitic stainless steel', *Machining Science and Technology*, Vol. 11, No. 2, pp.183-200.
- Churi, N.J., Li, Z.C., Pei, Z.J. and Treadwell, C. (2005) 'Rotary ultrasonic machining of titanium alloy: a feasibility study', *Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition, November 5–11, 2000, Orlando, FL, USA*.

- Churi, N.J., Pei, Z.J. and Treadwell C. (2006) 'Rotary ultrasonic machining of titanium alloy: effects of machining variables', *Machining Science and Technology*, Vol. 10, No. 3, pp. 301-321.
- Churi, N.J., Pei, Z.J. and Treadwell C. (2007a) 'Wheel wear mechanisms in rotary ultrasonic machining of titanium', *Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition, November 11–15, 2007, Seattle, WA, USA*.
- Churi, N.J., Pei, Z.J. and Treadwell C. (2007b) 'Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables', *International Journal of Precision Technology*, Vol. 1, No. 1, pp.85-96.
- Churi, N.J., Pei, Z.J., Treadwell C. and Shorter, D. (2007c) 'Rotary ultrasonic machining of silicon carbide: designed experiments', *International Journal of Manufacturing Technology and Management*, Vol. 12, No. 1-3, pp.284-287.
- Cong, W.L., Pei, Z.J., Churi, N.J. and Wang, Q.G. (2009a) 'Rotary ultrasonic machining of stainless steels: design of experiments', *Transactions of the North American Manufacturing Research Institution of SME*, Vol. 37, pp.261-268.
- Cong, W.L., Pei, Z.J., and Wang, Q.G. (2009b) 'Surface roughness in rotary ultrasonic machining of stainless steels', *Proceedings of the IIE Annual Conference and Expo 2009 – Innovations Revealed, May 30 - June 3, 2009, Miami, FL, USA*.
- Cong, W.L., Pei, Z.J., Van Vleet, E., Mohanty, N. and Treadwell, C. (2009c) 'Vibration amplitude in rotary ultrasonic machining: a novel measurement method and effects of process variables', submitted to *Journal of Manufacturing Science and Engineering*.

- Cong, W.L., Pei, Z.J., Denies, T., Nottingham, D., Zhang, P.F. and Treadwell, C. (2009d) 'Surface roughness in rotary ultrasonic machining: hypotheses and their testing via experiments', submitted to *Journal of Manufacturing Science and Engineering*.
- Deng, G.P., Li, S.Z., Wu, S.Q. and Yang, X.G. (1993) 'Ultrasonic vibration drilling of small-diameter deep holes of difficult-to-machine stainless steel: theoretical analysis and comparative experimental research', *Proceedings of the 1993 ASME Winter Annual Meeting, November 28 - December 3, 1993, New Orleans, LA, USA*, pp.835-839.
- Dolinsek, S. (2003) 'Work-hardening in the drilling of austenitic stainless steels', *Journal of Materials Processing Technology*, Vol. 133, No. 1-2, pp.63-70.
- Hu, P., Zhang, J.M., Jiao, Y., Pei, Z.J. and Treadwell, C. (2003) 'Experimental investigation on coolant effects in rotary ultrasonic machining', *Proceedings of the NSF Workshop on Research Needs in Thermal Aspects of Material Removal Processes, June 10-12, 2003, Stillwater, OK, USA*, pp. 340-345.
- Jiao, Y., Hu, P., Pei, Z.J. and Treadwell, C. (2005a) 'Rotary ultrasonic machining of ceramics: design of experiments', *International Journal of Manufacturing Technology and Management*, Vol. 7, No. 2-4, pp.192-206.
- Jiao, Y., Liu, W.J., Pei, Z.J., Xin, X.J. and Treadwell, C. (2005b) 'Study on edge chipping in rotary ultrasonic machining on ceramics: an integration of designed experiment and FEM analysis', *Journal of Manufacturing Science and Engineering*, Vol. 127, No. 4, pp.752-758.
- Jing, L.L., Li, Z.Y., Chen, M., Sun, F.H., Hu, Z.G., Zhu, X.F., Li, Z.W. and Xu, H. (2005) 'Experimental study on the cutting deformation in drilling austenitic stainless steel', *Journal of Shanghai Jiaotong University*, Vol. 39, No. 11, pp.1746-1750 (in Chinese).

- Khanna, N., Pei, Z.J. and Ferreira, P.M. (1995) 'An experimental investigation of rotary ultrasonic grinding of ceramic disks', *Technical Papers of the North American Manufacturing Research Institution of SME*. pp.67–72. also SME Technical Paper, MR95–141, Society of Manufacturing Engineers, Dearborn, MI, USA.
- Kosmol, J., Czech, M., Klarecki, K. and Sliwka, J. (1999) 'Optimisation of drills for the machining of austenitic steel', *Journal of Materials Processing Technology*, Vol. 89-90, pp.117-122.
- Kubota, M., Tamura, Y. and Shimamura, N. (1997) 'Ultrasonic machining with a diamond impregnated tool', *Bulletin Japan Society of Precision Engineering*, Vol. 11, No. 3, pp.127–132.
- Legge, P. (1964) 'Ultrasonic Drilling of Ceramics', *Industrial Diamond Review*, Vol. 24, No. 278, pp.20–24.
- Li, X.K., Chen, Z.B., Chen, M., Hu, Z.G., Zhu, X.F. and Li, Z.W. (2006a) 'Research on wear mechanism of coated HSS drills during machining stainless steel', *China Mechanical Engineering*, Vol. 17, No. 4, pp.354-361 (in Chinese).
- Li, Z.C., Cai, L.W., Pei, Z.J. and Treadwell, C. (2006b) 'Edge-chipping reduction in rotary ultrasonic machining of ceramics: finite element analysis and experimental verification', *International Journal of Machine Tools and Manufacture*, Vol. 46, No. 12-13, pp.1469-1477.
- Li, Z.C., Jiao, Y., Deines, T.W., Pei, Z.J. and Treadwell, C. (2004) 'Experimental study on rotary ultrasonic machining (RUM) of poly crystalline diamond compacts (PDC)', *Proceedings of IIE Annual Conference and Exhibition, May 15–19, 2004*, Houston, TX, USA.

- Li, Z.C., Jiao, Y., Deines, T.W., Pei, Z.J. and Treadwell, C. (2005a) 'Development of an innovative coolant system for rotary ultrasonic machining', *International Journal of Manufacturing Technology and Management*, Vol. 7, No. 2-4, pp.318-328.
- Li, Z.C., Jiao, Y., Deines, T.W., Pei, Z.J. and Treadwell, C. (2005b) 'Rotary ultrasonic machining of ceramic matrix composites: Feasibility study and designed experiments', *International Journal of Machine Tools and Manufacture*, Vol. 45, No. 12-13, pp.1402-1411.
- Li, Z.C., Pei, Z.J., Zeng, W.M., Kwon, P. and Treadwell, C. (2005c) 'Preliminary experimental study of rotary ultrasonic machining on zirconia toughened alumina', *Transactions of North American Manufacturing Research Institution /SME*, Vol. 33, pp.89-96.
- Li, Z.C., Pei, Z.J., Sisco, T., Micale, A.C. and Treadwell, C. (2007) 'Experimental study on rotary ultrasonic machining of graphite/epoxy panel', *Proceedings of the ASPE 2007 Spring Topical Meeting on Vibration Assisted Machining Technology, April 16-17, 2007*, Chapel Hill, NC, USA, pp.52-57.
- Liu, G., Chen, M., Jing, L.L., Hu, Z.G., Zhu, X.F., Li, Z.W. and Xu, H. (2006) 'The development of special drills for high-efficient drilling austenitic stainless steel - part I: drill comparison and experiment research', *Key Engineering Materials*, Vol.315-316, pp. 195-199.
- Markov, A. and Ustinov, I. (1972) 'A study of the ultrasonic diamond drilling of non-metallic materials', *Industrial Diamond Review*, No. March, pp.97-99.
- Markov, A. (1977) 'Ultrasonic drilling and milling of hard non-metallic materials with diamond tools', *Machine and Tooling*, Vol. 48, No. 9, pp.45-47.
- Pei, Z.J. (1995) *Rotary Ultrasonic Machining of Ceramics: Characterization and Extensions*. PhD thesis. University of Illinois at Urbana-Champaign, Illinois, USA.

- Pei, Z.J. and Ferreira, P.M. (1998) 'Modeling of ductile mode material removal in rotary ultrasonic machining', *International Journal of Machine Tools and Manufacture*, Vol. 38, No. 10-11, pp.1399-1418.
- Pei, Z.J. and Ferreira, P.M. (1999) 'An experimental investigation of rotary ultrasonic face milling', *International Journal of Machine Tools and Manufacture*, Vol. 39, No. 8, pp.1327-1344.
- Pei, Z.J., Ferreira, P.M. and Haselkorn, M. (1995a) 'Plastic flow in rotary ultrasonic machining of ceramics', *Journal of Materials Processing Technology*, Vol. 48, No. 1-4, pp.771-777.
- Pei, Z.J., Ferreira, P.M., Kapoor, S.G. and Haselkorn, M. (1995b) 'Rotary ultrasonic machining for face milling of ceramics', *International Journal of Machine Tools and Manufacture*, Vol. 35, No. 7, pp.1033-1046.
- Pei, Z.J., Prabhakar, D., Ferreira, P. and Haselkorn, M. (1995c) 'Mechanistic approach to the prediction of material removal rates in rotary ultrasonic machining', *Journal of Engineering for Industry*, Vol. 117, No. 2, pp.142-151.
- Petrukha, P.G. (1970) 'Ultrasonic diamond drilling of deep holes in brittle materials', *Russian Engineering Journal*, Vol. 50, No. 10, pp.70-74.
- Prabhakar, D. (1992) *Machining Advanced Ceramic Materials Using Rotary Ultrasonic Machining Process*. M.S. Thesis. University of Illinois at Urbana-Champaign, Illinois, USA.
- Prabhakar, D., Ferreira, P.M. and Haselkorn, M. (1992) 'An experimental investigation of material removal rates in rotary ultrasonic machining', *Transactions of the North American Manufacturing Research of SME*, Vol. 20, pp.211-218.

- Prabhakar, D., Pei, Z.J., Ferreira, P.M. and Haselkorn, M. (1993) 'A theoretical model for predicting material removal rates in rotary ultrasonic machining of ceramics', *Transactions of North American Manufacturing Research Institution of SME*, Vol. 21, pp.167–172.
- Treadwell, C. and Pei, Z.J. (2003) 'Machining ceramics with rotary ultrasonic machining', *Ceramic Industry*, Vol. 153, No. 6, pp.39-42.
- Tyrrell, W.R. (1970a) 'Rotary ultrasonic machining', *SME Technical Paper*, No. MR70-516.
- Tyrrell, W.R. (1970b) 'New method for machining hard and brittle materials', *SAMPE Quarterly*, Vol. 1, No. 2, pp.55-59.
- Uhlmann, E., Spur, G. and Holl, S.E. (1999) 'Machining of complex contours by ultrasonic assisted grinding', *SME Technical Paper*, No. MR99-284, pp.1-13, *3rd International Machining and Grinding Conference*, Cincinnati, OH, USA.
- Urmann, D.H. (2008). Useful Applications of Stainless Steel. Obtained through the Internet: <http://www.articlesbase.com/home-improvement-articles/useful-applications-of-stainless-steel-587256.html>, [accessed 1/1/2009].
- Wang, H. and Lin, L. (1993) 'Improvement of rotary ultrasonic deep hole drilling of glass ceramics – zerodur', *Seminar presentated at the 7th International Precision Engineering*, May, Kobe, Japan.
- Ya, G., Qin, H.W., Yang, S.C. and Xu, Y.W. (2002) 'Analysis of the rotary ultrasonic machining mechanism', *Journal of Materials Processing Technology*, Vol. 129, No. 1-3, pp.182-185.
- Ya, G., Qin, H.W., Xu, Y.W. and Zhang, Y.S. (2001) 'An experimental investigation on rotary ultrasonic machining', *Key Engineering Materials*, Vol. 202–203, pp.277–280.

- Zeng, W.M., Li, Z.C., Pei, Z.J. and Treadwell, C. (2004) Experimental investigation into rotary ultrasonic machining of alumina. *CD-ROM Proceedings of the International Mechanical Engineering Congress and Exposition*, November 13–19, 2004, Anaheim, CA.
- Zeng, W.M., Li, Z.C., Pei, Z.J. and Treadwell, C. (2005) ‘Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics’, *International Journal of Machine Tools and Manufacture*, Vol. 45, No. 12-13, pp.1468-1473.
- Zhang, Q.H., Wu, C.L., Sun, J.L. and Jia, Z.X. (2000) ‘Mechanism of material removal in ultrasonic drilling of engineering ceramics’, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 214, No. 9, pp.805-810.
- Zhong, J.W., Ma, Y.P., Sun, F.H. and Chen M. (2004) ‘Research on high-speed drilling performances of austenitic stainless steels’, *Journal of Shanghai Jiaotong University*, Vol. 38, No. 2, pp.83-88 (in Chinese).

Chapter 6 - Aerospace Stainless Steel - Comparison of Superabrasive Tools

Paper title:

Rotary ultrasonic machining of stainless steels: empirical study of machining variables

Published in:

Proceedings of the ASME 2010 International Manufacturing Science and Engineering Conference (MSEC-2010), October 12-15, 2010, Erie, PA, USA.

Authors' names:

Cong, W.L.¹, Feng, Q.¹, Pei, Z.J.¹, and Treadwell, C.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

2. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Many experiments on rotary ultrasonic machining (RUM) have been conducted to study how input variables (including tool rotation speed, ultrasonic power, feedrate, and abrasive size) affect output variables (such as cutting force, torque, surface roughness, and edge chipping) by using diamond tools. However, a literature review has revealed that there is no reported study on CBN tools in RUM. This paper, for the first time in literature, presents an investigation of RUM of stainless steel using CBN tools. Firstly, an introduction of superabrasive materials and RUM principle was provided. After presenting the experiment procedures and workpiece properties, it reports the results on tool wear, cutting force, torque, surface roughness in RUM of stainless. Finally, it discusses and compares the performances of diamond and CBN tools in RUM of stainless steel under certain conditions.

Keywords: Superabrasive, CBN, Diamond, Rotary ultrasonic machining, Stainless steel, Tool wear, Cutting force, Torque, Surface roughness.

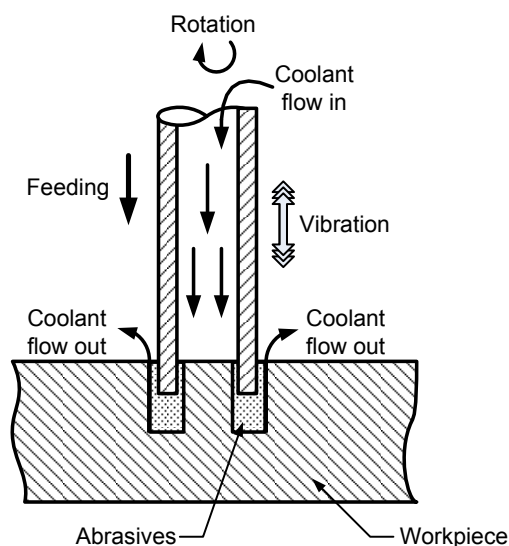
6.1 Introduction

Rotary ultrasonic machining (RUM) is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. Figure 6.1 illustrates the RUM process. A rotating core drill with a metal-bonded abrasive tool tip is ultrasonically vibrated (at a frequency of 20 kHz) in its axial direction and fed downwards to the workpiece at a constant feedrate or under a constant pressure. A coolant is pumped through the core of the drill to wash away swarfs, prevent jamming of the drill, and keep the drill cool.

RUM has been used to drill a variety of materials, and all reported RUM experiments were conducted using diamond tools [1-18]. This paper, for the first time, reports the RUM experiment using CBN tools. Recently, there are papers that studied effects of spindle speed,

feedrate, and ultrasonic power on cutting force, torque, and surface roughness in RUM of stainless [4-6].

Figure 6.1 Illustration of RUM.



Stainless Steels are widely utilized in aerospace, chemical and medical industries [19,20]. Characteristics of stainless steels, such as high ductility, poor thermal conductivity and severe strain hardening, can lead to high temperature and cutting force during machining. As a result, efficiency and tool life are low when drilling stainless steels in many cases of production [19-23].

Composite/steel stacks are used increasingly in newer generations of aircraft. This has resulted in greater challenges to twist drilling. Twist drills wear quickly when drilling composite materials and they often produce burrs at both entrance and exits side of the holes in stainless steel. Frequently, subsequent processes are needed to remove these burrs. It has been shown that RUM can effectively drill composite materials [24]. These results indicate that RUM can be a better alternative to drill composite/steel.

Superabrasive materials include diamond and cubic boron nitride (CBN). Diamond is the hardest known material and CBN is the second [25-27]. Hardness ratio between diamond and

CBN is 1 : 0.58~0.64 [26]. Diamond abrasives, both nature and synthetic, are widely used for grinding various type of materials including cemented carbide, ceramic, glasses, composites, metals, etc. In spite of its extreme hardness, diamonds had been found uneconomical for grinding of most ferrous metals (except for some hard cast iron), owing to graphitization and carbon diffusion into the iron causing excessive diamond wear [25,26]. Malkin and Guo [25] claimed that “Degradation of diamond appears to be more rapid in the presence of iron and other ferrous metals unsaturated in carbon, owing to their affinity for carbon. CBN, although somewhat softer than diamond, is more chemically stable at higher temperatures and wears much less on most ferrous metals”. CBN has emerged as an important alternative superabrasive for grinding of steels and some non-ferrous high strength alloy. In comparison with diamond, one important advantage of CBN is its thermal stability [25,26]. It is desirable to compare the performance of CBN and diamond tool in RUM of stainless steel.

This paper is to compare tool wear, cutting force, torque, and surface roughness in RUM of stainless steel using CBN and diamond abrasive tools. There are five sections in this paper. The reminder of this paper is organized as following. Section 6.2 describes experimental procedures, conditions, and workpiece properties. Section 6.3 - 6.6 present experimental results on tool wear, cutting force, torque, and surface roughness, respectively. Conclusions are drawn up in Section 6.7.

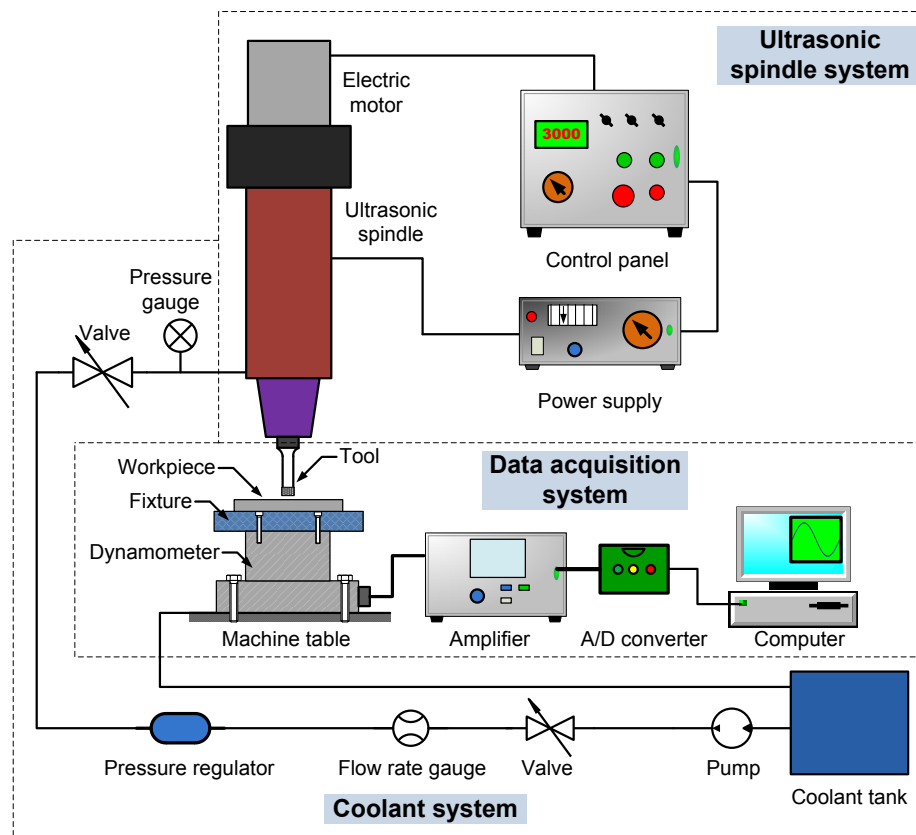
6.2 Experimental conditions and procedures

6.2.1 Experimental set-up and conditions

The machining experiments were performed on a Sonic-Mill Series 10 RUM machine (Sonic-Mill, Albuquerque, NM, USA). The experiment set-up is shown in Figure 6.2. It mainly

consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system comprised an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converted low frequency (60 Hz) electrical supply into high frequency (20 kHz) AC output. This AC output was converted into mechanical vibrations by the piezoelectric converter in the ultrasonic spindle. The motor attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds could be obtained by adjusting the motor speed controller.

Figure 6.2 Experimental set-up.



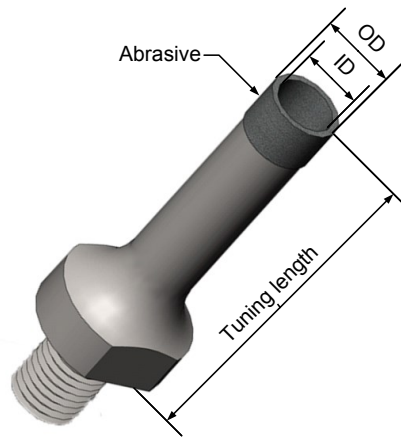
The experimental conditions are listed in Table 6.1. Two holes were drilled for each type of the tool under each of these experimental conditions. The reported tool wear and cutting force

data were those of the first hole drilled by each tool. The reported torque and surface roughness values were the average values for the two holes.

Table 6.1 Experimental conditions.

Parameter	Unit	Value
Tool rotation speed	rpm	3000
Feedrate	mm/s	0.01
Ultrasonic power	%	20

Figure 6.3 Illustration of RUM tool.



The CBN and diamond metal-bonded tools were provided by NBR Diamond tool Corp. (LaGrangeville, NY, USA). Both CBN and diamond tools had the same geometry which is shown in Figure 6.3. The tools had a tuning length of 60 mm, outer diameter (OD) of 12.7 mm, and inner diameter (ID) of 10.2 mm. The size of abrasives was mesh 60/80.

Water-soluble Quakercool 6010 cutting fluid (Murdock Industrial Supply Co., Wichita, KS, USA) was used as coolant and diluted with water at a ratio of 1 to 14. The workpiece material was 15-5 stainless steel. The size of workpiece was $150 \times 125 \times 12.7$ mm. The properties of the stainless steel are listed in Table 6.2.

Table 6.2 Properties of stainless steel (15-5).

Property	Unit	Value
Density	g/cm ³	7.8
Elastic modulus	MPa	196×103
Ultimate tensile strength	MPa	1350 ± 50
Yield strength	MPa	1200 ± 50
Hardness	HRC	40~44
Thermal conductivity	W/m·K	17.9
Specific Heat	kJ/kg·K	0.47

6.2.2 Measurement procedure

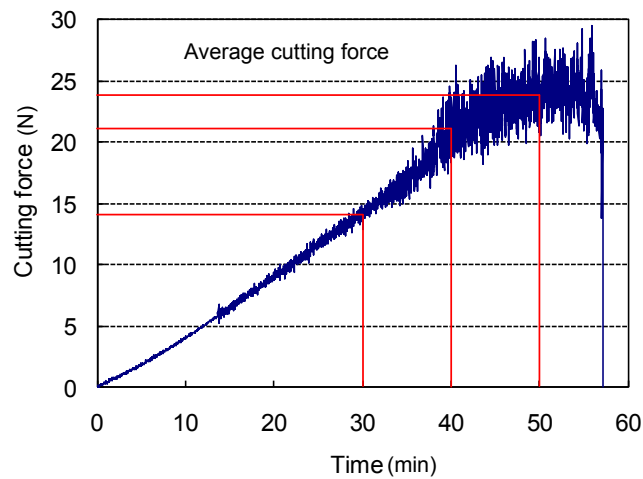
An optical microscope (Model BX51 Olympus Inc. Tokyo, Japan) was used to observe the abrasive grains of the tools. The eyepiece of the microscope had a magnification of 10 and the objective lens had a magnification of 5. Thus, the total magnification was 50.

The weight loss of the tool during each test was the difference between the tool weight measurements before and after the test. The tools were cleaned by using methanol and acetone before measurement to remove any coolant and oil left on the tool after the test and were dried by using a hand dryer. The weight was measured using a high accuracy scale (Model APX-200, Denver Instrument, Denver, CO, USA).

The cutting force and torque measurement system included a dynamometer, an amplifier, an A/D converter, and a computer with software. The dynamometer was Kistler 9272 (Kistler Instrument Corp, Amherst, NY, USA). The workpiece was clamped by a fixture amounted on top of the dynamometer. The electrical signals from the dynamometer were transformed into digital signals by an A/D converter. Then the digital signals were saved on a computer with the help of Lab-VIEW (Version 5.1, National Instruments, Austin, TX, USA). The measurements average cutting forces are demonstrated in Figure 6.4. The plot of cutting force versus time shows a wave shape. The cutting force reported in this paper is the average cutting force (i.e. the

mean line of the wave during the drilling process). The torque value reported was the maximum value during the drilling process.

Figure 6.4 Schematic illustration of cutting force measurement.



Surface roughness (R_a) was measured with a surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan). The test range was set at 4 mm and cut-off length was set at 0.8 mm. The surface roughness in this study was characterized by R_a , average surface roughness. As shown in Figure 6.5, roughness was measured at two locations of the machined hole and rod, near the entrance side and near the exit side. At each location, four measurements were performed with 90 degrees between two adjacent measurements. Each measurement was repeated once. The reported R_a value for each location was the average of these eight collected data.

Figure 6.5 Illustration of surface roughness measurement.

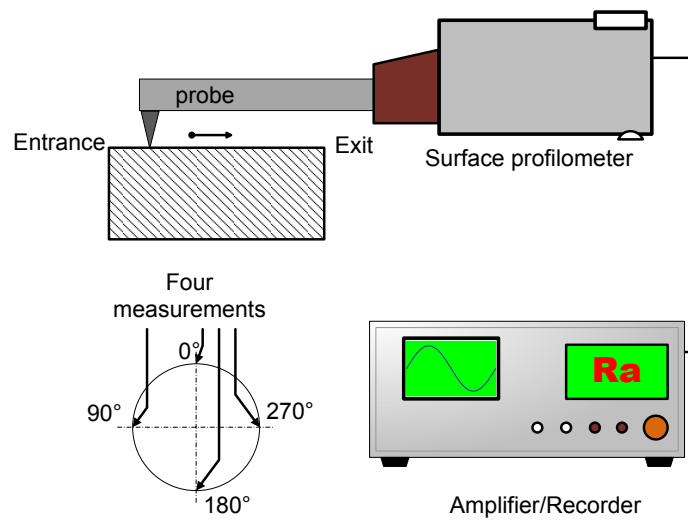
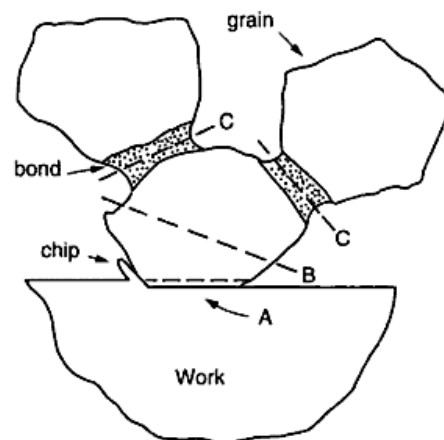


Figure 6.6 Illustration of wear mechanism for fixed abrasive tools (after[19-22]).



6.3 Comparison of tool wear

Weight loss of the tool can be used to represent tool wear. Weight loss is predominantly determined by grain fracture and bond fracture whereas attritious wear contributes little [25-28]. From Table 6.3, it can be seen that the wear of the diamond tool was much less than the CBN tool.

Table 6.3 Tool weight data before and after test.

Abrasive type	Before test (g)	After test (g)	Weight loss (g)
CBN	36.4234	36.3755	0.0479
Diamond	36.8285	36.8233	0.0052

Tool wear is an extremely complex process. It is generally recognized that there are three main mechanisms of tool wear for fixed abrasive tools as illustrated in Figure 6.6: attritious wear, grain fracture, and bond fracture. A fixed abrasive tool consists of an agglomeration of hard abrasive grains held together by a weaker bond material [25].

Figure 6.7 and Figure 6.8 show the topography of the tool end faces before and after test. A certain amount of material was removed from the CBN grains making the top surface to be flat after drilling one hole. The CBN tool had more attritious wear and cracking (grain fracture) on several grains. In contrast, the diamond tool only had some negligible attritious wear on a few grains. No grain dislodgment or bond fracture could be observed on the diamond tool after drilling one hole. However, on the CBN tool, a certain amount of metal bond material was removed leading to the grain to be completely pulled out leaving a cavity in the metal bond after drilling one hole.

Figure 6.7 Attritious wear on end faces of CBN and diamond tool.

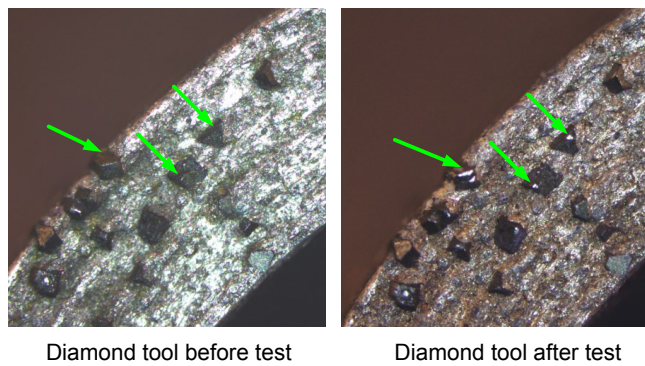
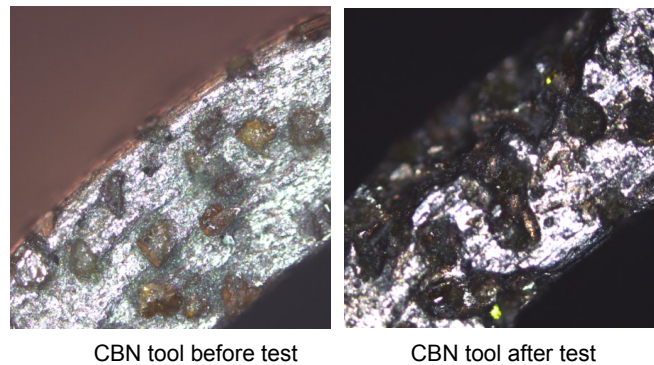


Figure 6.8 Fracture wear on the end faces of CBN tool.

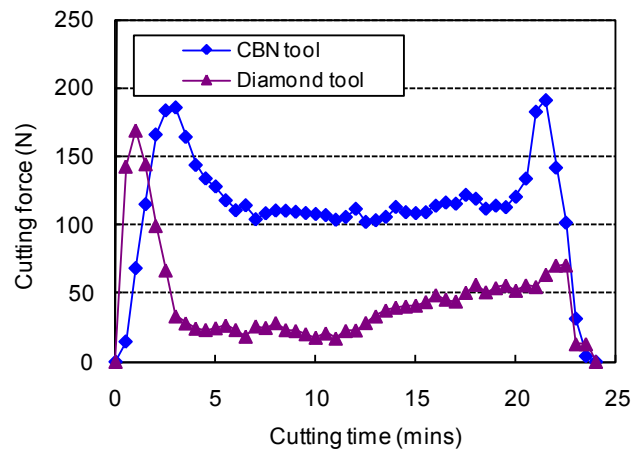


6.4 Comparison of cutting force

The relationship between the cutting force and cutting time is shown in Figure 6.9. As the experiment proceeded, for both CBN tool and diamond tool, the cutting forces increased remarkably in the first several minutes, and then decreased rapidly in the next few minutes. From around 5 minutes to around 20 minutes, the increases in the cutting forces for both tools are small. However, beginning at 20 minutes, for the CBN tool, the cutting force had a considerable increase in a short time. In the whole process, the cutting force of diamond tool was remarkably smaller than that of the CBN tool, except in the first few minutes, where the cutting force of the diamond tool is higher than that of the CBN tool. The total maximum cutting force using CBN tool (191 N) is larger than that using diamond tool (168 N).

The cutting temperature was relative low in this process, so the diamond may not be degraded. The hardness of the CBN is about 3/4 the hardness of the diamond abrasives. During the machining process, the CBN abrasive is easy to break. In this case, CBN tool showed inferior results.

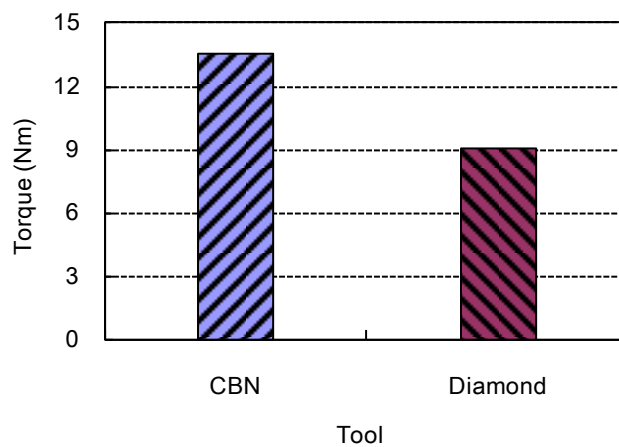
Figure 6.9 Cutting force versus cutting time.



6.5 Comparison of torque

The maximum torque values of CBN tool and diamond tool in this experiment are plotted in Figure 6.10. The diamond tool resulted in a smaller torque value. From previous sections, it was observed that plenty of CBN abrasive grains were dulled and flatted during machining. In addition, the cutting force was higher with the CBN tool.

Figure 6.10 Results on torque with CBN and diamond tools.



6.6 Comparison of surface roughness

Figure 6.11 and Figure 6.12 show the experimental data of surface roughness at both entrance and exit locations of holes and rods, respectively. It can be observed that the surface roughness when using the CBN tool was lower than that when using the diamond tool for both entrance and exit locations of holes and rods. In comparison to the CBN tool, larger variation of surface roughness was also observed at different locations with the diamond tool. The surface roughness values at the entrance location were usually lower than those at the exit location for both hole and rod. This is consistence with the results stated by Cong et al. [7].

The hardness of CBN is about 3/4 of the hardness of the diamond abrasives. During the machining process, the CBN abrasives will be easy to wear and flat. By comparison, the diamond abrasives are sharper. Sharper abrasive usually get higher surface roughness.

Figure 6.11 Effects on surface roughness of the machined hole.

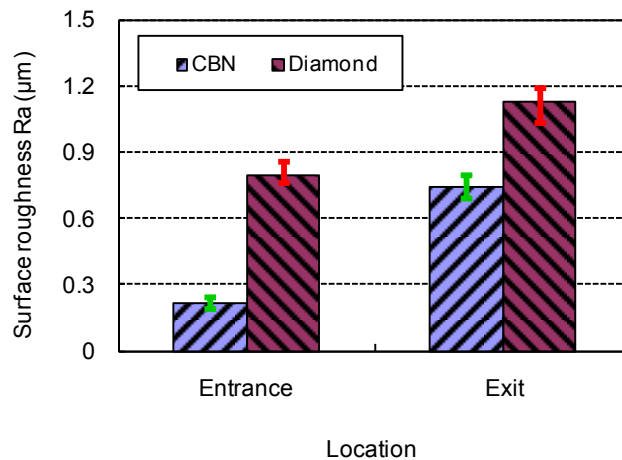
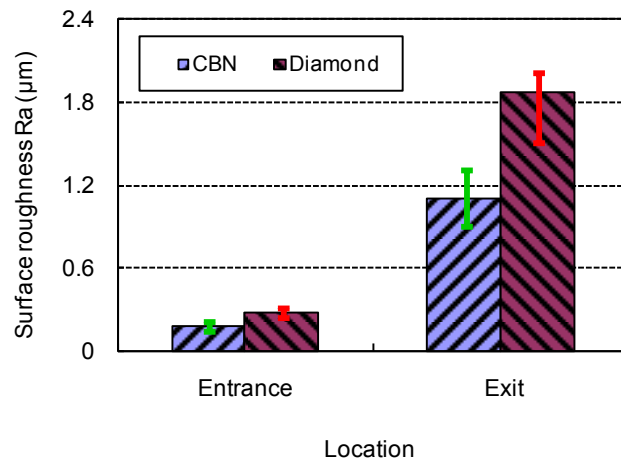


Figure 6.12 Effects on surface roughness of the machined rod.



6.7 Conclusions

RUM of stainless steel with CBN and diamond tools has been conducted. The effects of different abrasive grains on tool wear, cutting force, torque, and surface roughness have been investigated. The following conclusions can be drawn:

- (1). The CBN tool had more severe wear than the diamond tool under the experimental conditions used in this study. Attritious wear, grain fracture, and bond fracture were observed at the end face of the CBN tool. Only slight attritious wear was observed on some diamond grains.
- (2). The CBN tool had larger cutting force and torque than the diamond tool during the RUM of stainless steel under the experimental conditions in this study.
- (3). The CBN tool produced lower surface roughness on the machined hole and rod than the diamond tool.

Acknowledgements

The work was supported by the National Science Foundation through Award CMMI-0900462. The authors would like to thank Mr. Bruno Renzi at NBR Diamond Tool Corporation for providing the diamond tools.

References

- [1] Churi, N. J., Pei, Z. J., and Treadwell, C., 2006, "Rotary ultrasonic machining of titanium alloy: effects of machining variables," *Machining Science and Technology*, **10**(3), pp. 301–321.
- [2] Churi, N. J., Pei, Z. J., and Treadwell, C., 2007, "Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables," *International Journal of Precision Technology*, **1**(1), pp. 85–96.
- [3] Churi, N. J., Pei, Z. J., Treadwell, C., and Shorter, D., 2009, "Rotary ultrasonic machining of dental ceramics," *International Journal of Machining and Machinability of Materials*, **6**(3–4), pp. 270–284.
- [4] Cong, W. L., Pei, Z. J., and Wang, Q. G., 2009, "Surface roughness in rotary ultrasonic machining of stainless steels," *Proceedings of the IIE Annual Conference and Expo 2009 – Innovations Revealed*, 30 May–3 June, Miami, FL, USA.
- [5] Cong, W. L., Pei, Z. J., Churi, N. J., and Wang, Q. G., 2009, "Rotary ultrasonic machining of stainless steels: design of experiments," *Transactions of the North American Manufacturing Research Institution of SME*, **37**, pp. 261–268.
- [6] Cong, W. L., Pei, Z. J., Deines, T., Wang, Q. G., and Treadwell, C., 2010, "Rotary ultrasonic machining of stainless steels: empirical study of machining variables," *International Journal of Manufacturing Research*, **5**(3), pp. 370–386.

- [7] Cong, W. L., Pei, Z. J., Denies, T., Nottingham, D., Zhang, P. F., and Treadwell, C., 2010, "Surface roughness in rotary ultrasonic machining: hypotheses and their testing via experiments," submitted to Journal of Manufacturing Science and Engineering.
- [8] Jiao, Y., Liu, W. J., Pei, Z. J., Xin, X. J., and Treadwell, C., 2005, "Study on edge chipping in rotary ultrasonic machining on ceramics: an integration of designed experiment and FEM analysis," Journal of Manufacturing Science and Engineering, **127**(4), pp. 752–758.
- [9] Jiao, Y., Hu, P., Pei, Z. J., and Treadwell, C., 2005, "Rotary ultrasonic machining of ceramics: design of experiments," International Journal of Manufacturing Technology and Management, **7**(2–4), pp. 192–206.
- [10] Khanna, N., Pei, Z. J., and Ferreira, P. M., 1995, "An experimental investigation of rotary ultrasonic grinding of ceramic disks," Technical Papers of the North American Manufacturing Research Institution of SME, pp. 67–72, also SME Technical Paper, MR95–141, Society of Manufacturing Engineers, Dearborn, MI.
- [11] Li, Z. C., Jiao, Y., Deines, T. W., Pei, Z. J., and Treadwell, C., 2004, "Experimental study on rotary ultrasonic machining (RUM) of poly crystalline diamond compacts (PDC)," CD-ROM Proceedings of the 13th Annual Industrial Engineering Research Conference (IERC–2004), Houston, TX, May 15–19.
- [12] Li, Z. C., Jiao, Y., Deines, T. W., Pei, Z. J., and Treadwell, C., 2005, "Rotary ultrasonic machining of ceramic matrix composites: feasibility study and designed experiments," International Journal of Machine Tools and Manufacture, **45**(12–13), pp. 1402–1411.
- [13] Li, Z. C., Pei, Z. J., Zeng, W. M., Kwon, P., and Treadwell, C., 2005, "Preliminary experimental study of rotary ultrasonic machining on zirconia toughened alumina,"

- Transactions of the North American Manufacturing Research Institution of SME, **33**, pp. 89–96.
- [14] Li, Z. C., Cai, L. W., Pei, Z. J., and Treadwell, C., 2006, “Edge-chipping reduction in rotary ultrasonic machining of ceramics: finite element analysis and experimental verification,” *International Journal of Machine Tools and Manufacture*, **46**(12-13), pp. 1469–1477.
- [15] Treadwell, C, and Pei, Z. J., 2003, “Machining ceramics with rotary ultrasonic machining,” *Ceramic Industry*, June, pp. 39–42.
- [16] Wang, Q. G., Cong, W. L., Pei, Z. J., Gao, H., and Kang, R.K., 2009, “Rotary ultrasonic machining of potassium dihydrogen phosphate (KDP) crystal: an experimental investigation on surface roughness,” *Journal of Manufacturing Processes*, **11**, pp. 66–73.
- [17] Zeng, W. M., Xu, X. P., and Pei, Z. J., 2009, “Experimental investigation of tool wear in rotary ultrasonic machining of alumina,” *Key Engineering Materials*, **416**, pp. 181–186.
- [18] Zeng, W. M., Li, Z. C., Pei, Z. J., and Treadwell, C., 2005, “Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics,” *International Journal of Machine Tools and Manufacture*, **45**(12–13), pp. 1468–1473.
- [19] Liu, G., Chen, M., Jing, L. L., Hu, Z. G., Zhu, X. F., Li, Z. W., and Xu, H., 2006, “The development of special drills for high-efficient drilling austenitic stainless steel – part I: drill comparison and experiment research”, *Key Engineering Materials*, **315–316**, pp. 195–199.
- [20] Dolinsek, S., 2003, “Work-hardening in the drilling of austenitic stainless steels”, *Journal Materials Processing Technology*, **133**(1–2), pp.63–70.

- [21] Zhong, J. W., Ma, Y. P., Sun, F. H., and Chen M., 2004, “Research on high-speed drilling performances of austenitic stainless steels”, *Journal of Shanghai Jiaotong University*, **38**(2), pp. 83–88 (in Chinese).
- [22] Jing, L. L., Li, Z. Y., Chen, M., Sun, F. H., Hu, Z. G., Zhu, X. F., Li, Z. W., and Xu, H., 2005, “Experimental study on the cutting deformation in drilling austenitic stainless steel”, *Journal of Shanghai Jiaotong University*, **39**(11), pp. 1746–1750 (in Chinese).
- [23] Kosmol, J., Czech, M., Klarecki, K., and Sliwka, J., 1999, “Optimisation of drills for the machining of austenitic steel”, *Journal Materials Processing Technology*, **89–90**, pp. 117–122.
- [24] Li, Z. C., Jiao, Y., Deines, T. W., Pei, Z. J. and Treadwell, C., 2005, “Rotary ultrasonic machining of ceramic matrix composites: Feasibility study and designed experiments”, *International Journal of Machine Tools and Manufacture*, **45**(12–13), pp. 1402–1411.
- [25] Malkin, S., and Guo, C. S., 2008, *Grinding Technology: Theory and Applications of Machining with Abrasives*, Second ed, Industrial Press, NY., Chap. 2 & 11.
- [26] Borkowski, J., and Szymanski, A., 1989, *Uses of Abrasives and Abrasive Tools*, PWN–Polish Scientific Publishers, Warsaw, Poland, Chap. 1 & 11.
- [27] Marinescu, I. D., Hitchiner, M., Uhlmann, E., Rowe W. B., and Inasaki, I., 2007, *Handbook of Machining with Grinding Wheels*, Second ed, CRC Press, Boca Raton, FL, Chap. 5 & 9.
- [28] Bhushan, B., 2002, *Introduction to Tribology*, John Wiley & Sons, Inc., New York, NY, Chap. 7.

Chapter 7 - Aerospace Stainless Steel - Design of Experiments on Cutting Force and Torque

Paper title:

Rotary ultrasonic machining of stainless steel: design of experiments

Published in:

Transactions of the North American Manufacturing Research Institution of SME (2009),
Vol. 37, pp. 261–268

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Churi, N.J.¹, Wang, Q.G.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State
University, Manhattan, KS 66506, USA

2. Key Laboratory of the Ministry of Education for Precision and Non-traditional
Machining Technology, Dalian University of Technology, Dalian, Liaoning, China

Abstract

Stainless steel has a variety of engineering applications due to its superior properties. Drilling is a commonly seen machining technique for stainless steels. Rotary Ultrasonic Machining (RUM) is one of the nontraditional machining processes for brittle materials and some metals. However, there is no report on RUM of stainless steel. This paper presents the results of a designed experiment investigation into RUM of stainless steel. A three-variable two-level full factorial design was employed to reveal main effects as well as interaction effects of three process variable (spindle speed, ultrasonic power, and feedrate). The process outputs studied include cutting force and torque.

Keywords: Stainless steel, Rotary ultrasonic machining, Cutting force, Torque

7.1 Introduction

Stainless steel is known for being tough and ductile with good strength. It is most often used for applications in high pressure corrosive environments and for aircraft components [Anonymous 2008, Liu et al. 2006].

In production practice, drilling is a commonly seen machining technique for stainless steel. However, austenite stainless steels' characteristics, such as poor thermal conductivity and severe hardening problem during machining, can lead to high temperature at drilling region and high cutting force on cutting-tools. As a result, in current industrial production, the drilling efficiency on stainless steel is low and cutting-tools cannot be used for long time [Zhong et al. 2004, Jing et al. 2005].

Twist drilling is a traditional drilling method for stainless steel. This method has been improved by giving the twist drills a TiN, TiAlN or TiCN coating and changing the point and helix angles [Jing et al. 2005, Li et al. 2006, Liu et al. 2006, Chen et al. 2006, Chen et al. 2007,

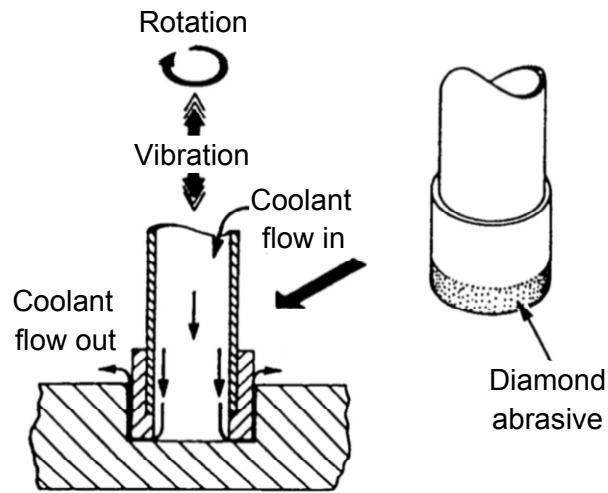
Deng et al. 1993]. However, no studies had been reported on using core drills with bonded diamond abrasives to drill stainless steel. For newer generations of aircraft, use of stainless steel/composite stacks presents new challenges to twist drilling, since composites tend to wear out twist drills much faster than stainless steel does [Margolis 2006]. In comparison, composites do not wear RUM cutting tools any faster than Ti does, since RUM uses grinding wheels with metal-bonded diamond abrasives.

Table 7.1 shows reported materials machined by RUM. It can be seen that RUM has been employed to machine many types of materials. However, no systematic studies have been published on RUM of stainless steel. In RUM, a rotating core drill with metal-bonded diamond abrasives is ultrasonically vibrated in the axial direction and feed towards the workpiece at a constant feedrate or constant force. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill and keeps it cool. This process is illustrated in Figure 7.1.

Table 7.1 Reported materials machined by RUM.

Material	Reference
Alumina	Tyrrell 1970, Zhang et al. 2000, Hu et al. 2003, Li et al. 2005, Zeng et al. 2004, Jiao et al. 2005
Beryllium oxide	Tyrrell 1970
Canasite	Khanna et al. 1995
Composites	Tyrrell 1970, Li et al. 2005, Li et al. 2007
Ferrite	Tyrrell 1970
Glass	Tyrrell 1970, Ya et al. 2002, Treadwell and Pei 2003
Polycrystalline diamond compact	Li et al. 2004
Silicon carbide	Zeng et al. 2005, Churi et al. 2007
Silicon nitride	Pei et al. 1995
Titanium	Churi et al. 2005, Churi et al. 2006, Churi et al. 2007
Uranium oxide cermet	Tyrrell 1970
Zirconia	Prabhakar 1992, Pei et al. 1995, Pei and Ferreira 1998, Pei and Ferreira 1999, Pei et al. 1995

Figure 7.1 Illustration of RUM.



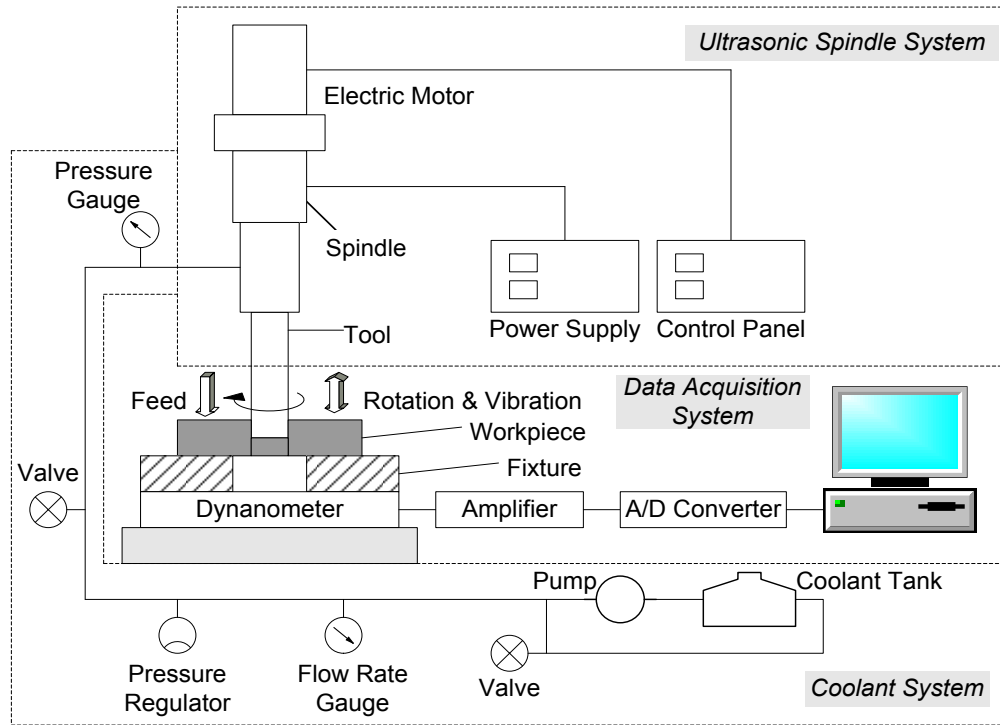
The objective of this study is to test the feasibility of RUM on stainless steel and to reveal the main effects and interaction effects on cutting force and torque.

7.2 Experimental set-up and procedure

7.2.1 Experimental conditions

The machining experiments were performed on a Sonic-Mill Series 10 RUM machine (Sonic-Mill, Albuquerque, NM, USA). The experiment set-up is shown in Figure 7.2. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle comprised of an ultrasonic spindle, a power supply, and a motor speed controller.

Figure 7.2 Experiment set-up.



A diamond core drill (NBR Diamond tool Corp., LaGrangeville, NY, USA) was used to drill the stainless steel workpieces. The outer and inner diameters of tool were 9.5 mm and 7.8 mm, respectively. The mesh size of the diamond abrasives was 80/100.

The water-soluble Quakercool 6010 cutting fluid (Murdock Industrial Supply Co., Wichita, KS, USA) was used as coolant and diluted with water at a ratio of 1 to 14.

The workpiece material was 15-5 stainless steel. The size of workpiece was $150 \times 125 \times 12.7$ mm.

7.2.2 Design of experiment

A 2^3 (two-level three-factor) full factorial design was employed. There were eight unique experiment conditions. Under each condition, the test was repeated once. The total number of test was 16. Based on the experience from preliminary experiments and due to the limitations of

the experimental set-up, the experiments were focused on the study of the following three process parameters or machining parameters:

- Spindle speed: rotational speed of cutting tool
- Ultrasonic power: percentage of power from ultrasonic power supply, which controls the ultrasonic vibration amplitude
- Feedrate: feedrate of cutting tool

Table 7.2 shows these variables and their values of the corresponding high and low levels.

Table 7.2 Low and high levels of process variables.

Process Variable	Unit	Low level (-)	High level (+)
Spindle speed	rpm	2500	3500
Feedrate	mm/s	0.01	0.02
Ultrasonic Power	%	20	35

The test matrix is shown in Table 7.3. The output variables (or the process output parameters) studied include cutting force (N) and torque (N·m).

Table 7.3 Test matrix and results.

Spindle speed	Feedrate	Ultrasonic power	Force (N)		Torque (N·m)	
			Test 1	Test 2	Test 1	Test 2
–	–	–	378	388	9.99	9.99
+	–	–	352	352	8.69	8.69
–	–	+	264	254	7.60	8.25
+	–	+	316	336	7.38	7.38
–	+	–	507	518	14.34	14.77
+	+	–	393	398	8.25	7.82
–	+	+	342	347	9.99	10.43
+	+	+	321	331	9.12	8.69

7.2.3 Measurement procedure

Cutting force and torque were measured by Kistler piezoelectric dynamometer (model 9272). The workpiece was clamped by a fixture amounted on top of the dynamometer. The electrical signals from the dynamometer were transformed into numerical signals by an A/D converter. Then the numerical signals to measure the cutting force were saved on a computer with the help of Lab-VIEW (Version 5.1, National Instruments, Austin, TX, USA). The sampling frequency to obtain the cutting force signals was 40 Hz. The cutting force and torque reported in this paper are the maximum cutting force and torque for each test. They are of the major concern because they determine the maximum stress in the workpiece, the maximum deflection or deformation of the machine, and the damage to the cutting tool.

7.3 Results of designed experiments

Experiment results are displayed in Table 7.3.

The software, DESIGN EXPERT (version 5.0, Stat-Ease Corporation, Minneapolis, MN, USA) was used to analyze the data. The software can perform ANOVA (analysis of variance) to identify the significant effects.

7.3.1 Main effects on cutting force

Figures 7.3-7.5 show the main effects of the three input parameters (spindle speed, ultrasonic power, and feedrate) on cutting force. According to ANOVA results, spindle speed, ultrasonic power, and feedrate all have significant effects on cutting force, with P-values < 0.00001. From Figures 7.3-7.5, it can be seen that cutting force increases as spindle speed and ultrasonic vibration power decrease, as feedrate increases. The effects of feedrate and spindle speed on cutting force had the trends that are consistent with those observed by Churi et al. (2007)

for RUM of SiC, by Jiao et al. (2005) for RUM of alumina, and by Li et al. (2005) for RUM of ceramic matrix composites. But the effect of ultrasonic power had a different trend from those reported previously with different workpiece materials.

Figure 7.3 Main effects of spindle speed on cutting force.

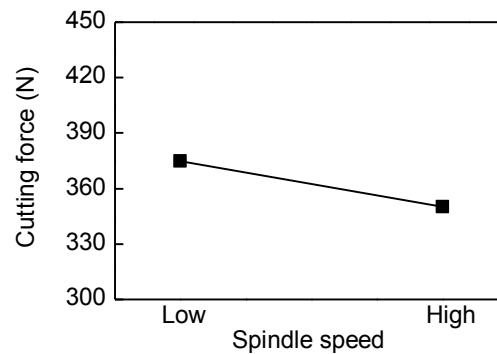


Figure 7.4 Main effects of ultrasonic power on cutting force.

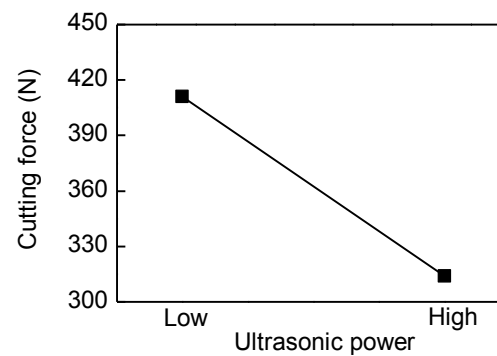
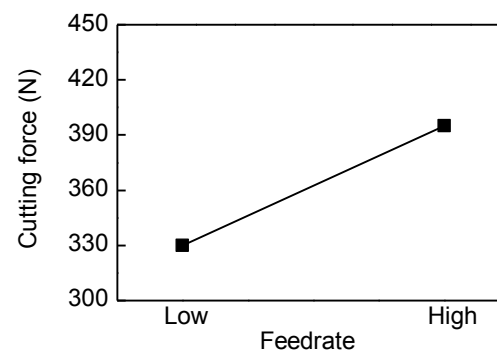


Figure 7.5 Main effects of feedrate on cutting force.



7.3.2 Two-factor interactions on cutting force

Three two-factor interaction effects can be obtained by the three-factor two-level factorial design. The results are plotted in Figures 7.6-7.8. All these three interactions have significant effects. Figure 7.6 shows the interaction between ultrasonic power and spindle speed (P-value < 0.00001). It can be seen that at the low level of ultrasonic power, cutting force increases at a higher rate with the increase of spindle speed, while at the high level of ultrasonic power, cutting force increases at a lower rate with the increase of spindle speed.

The interaction between spindle speed and feedrate (P-value < 0.00001) is shown in Figure 7.7. With increase of spindle speed, cutting force decreases at the high level of feedrate but increases at the low level of feedrate.

The interaction between ultrasonic power and feedrate (P-value = 0.00002) is shown in Figure 7.8. It can be seen that, with the increase of ultrasonic power, cutting force decreases at both high and low levels of feedrate but with different slopes.

Figure 7.6 Interaction effects between spindle speed and ultrasonic power on cutting force.

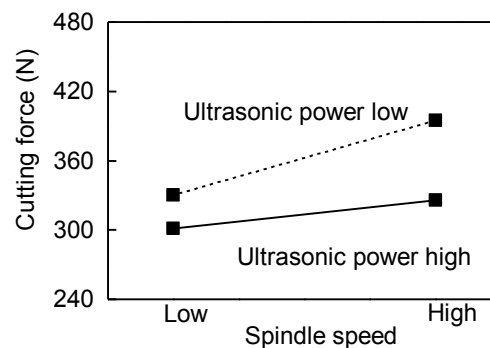


Figure 7.7 Interaction effects between spindle speed and feedrate on cutting force.

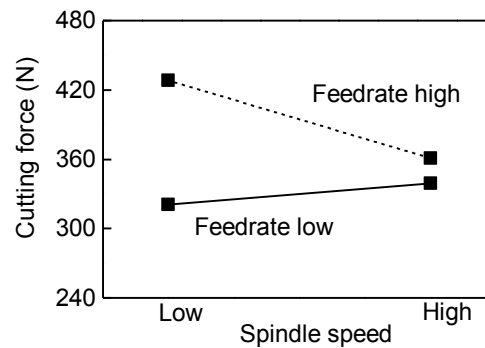
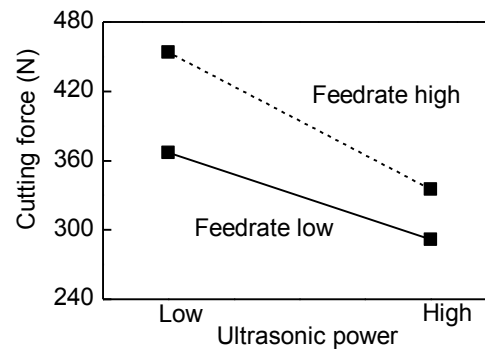


Figure 7.8 Interaction effects between ultrasonic power and feedrate on cutting force.



7.3.3 Three-factor interaction on cutting force

ANOVA results show that the three-factor interaction does not have significant effects on cutting force.

7.3.4 Main effects on torque

Main effects of the three input parameters (spindle speed, ultrasonic power, and feedrate) on torque are shown in Figures 7.9-7.11. P-values of these three effects are less than 0.00001. From these figures, the torque decreases with increase of spindle speed and ultrasonic power, and decrease of feedrate.

Figure 7.9 Main effects of spindle speed on torque.

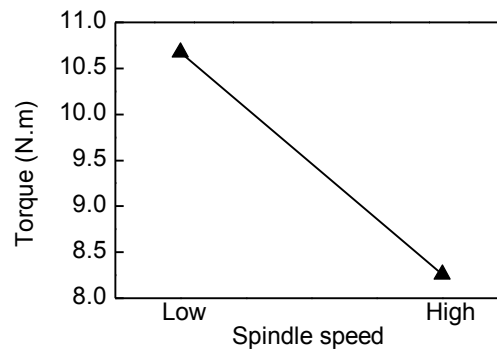


Figure 7.10 Main effects of ultrasonic power on torque.

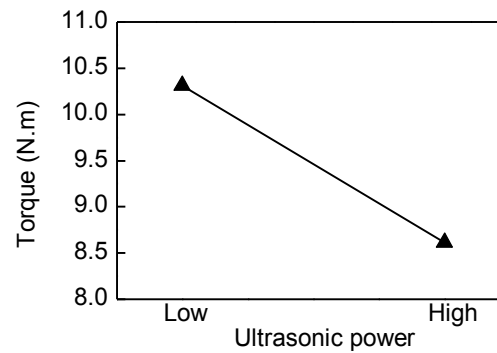
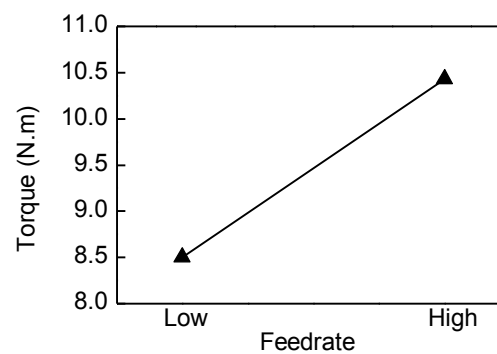


Figure 7.11 Main effects of feedrate on torque.



7.3.5 Two-factor interactions on torque

Two of the two-factor interactions have significant effects: the interaction between spindle speed and ultrasonic power and the interaction between spindle speed and feedrate (P-

value < 0.00001), as shown in Figure 7.12 and Figure 7.13. For the interaction between spindle speed and ultrasonic power, the torque decreases with increase of spindle speed at both high and low levels of ultrasonic power. However, the torque decreases at a faster rate for the low level of ultrasonic power. For the interaction between spindle speed and feedrate, the torque decreases with increase of spindle speed at both levels of feedrate. The decrease of torque at the high level of feedrate has a larger slope than that at the low level.

The interaction between ultrasonic power and feedrate does not have significant effects on torque.

Figure 7.12 Interaction effects between spindle speed and ultrasonic power on torque.

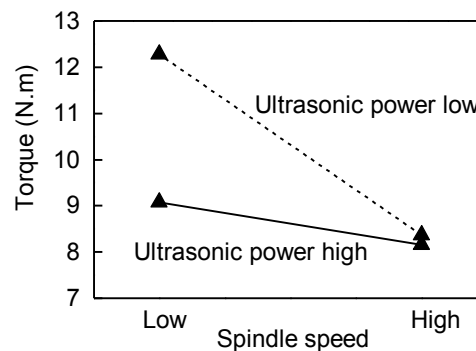
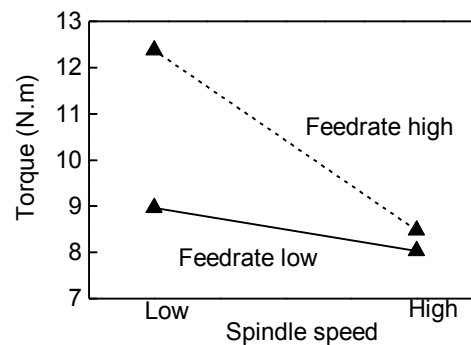


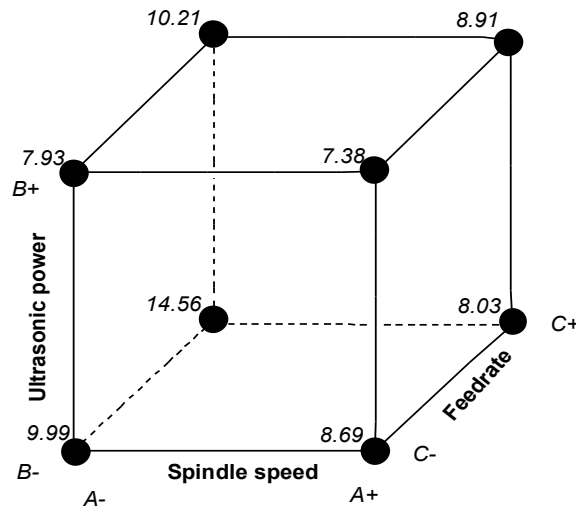
Figure 7.13 Interaction effects between spindle speed and feedrate on torque.



7.3.6 Three-factor interaction on torque

The three-factor interaction (P-value < 0.00001) of spindle speed, ultrasonic power, and feedrate on torque is significant. As shown in Figure 7.14, the best combination (when the torque is the smallest) is high spindle speed, high ultrasonic power, and low feedrate.

Figure 7.14 Three-factor interaction effects on torque.



7.4 Conclusions

In the present paper, rotary ultrasonic machining (RUM) using a diamond tool was introduced into drilling stainless steel for the first time. 2^3 (two-level, three-factor) full factorial design was employed to study the relationships between the output parameters (cutting force, torque) and three process variables (spindle speed, ultrasonic power, and feedrate). Based on the experiment results, this paper reports the main effects, two-factor interactions and three-factor interactions of these three process parameters on these output parameters.

The following conclusions are drawn from this study:

- (a) For cutting force, spindle speed, ultrasonic power, and feedrate have significant effects; higher spindle speed, higher ultrasonic power, and lower feedrate lead to a smaller cutting force.
- (b) All two-factor interactions have significant effects on cutting force.
- (c) For torque, spindle speed, ultrasonic power, and feedrate have significant effects; higher spindle speed, higher ultrasonic power, and lower feedrate lead to a smaller torque.
- (d) Some two-factor interactions have significant effects on torque.
- (e) The three-factor interaction also has significant effects on torque.

Acknowledgements

The authors would like to thank Mr. Bruno Renzi at NBR Diamond Tool Corporation for providing the diamond tool, Mr. Clyde Treadwell for providing technical assistance on RUM machine, and Mr. Timothy Denies at Kansas State University for providing technical assistance in making fixture and setting up the RUM machine.

References

- Anonymous. 15-5 stainless steel. in Specialty Steel Supply Company [database online]. 2007 Available at <http://www.specialtysteelsupply.com/15-5-stainless-steel.php>.
- Chen, M., G. Liu, L. L. Jing, Z. G. Hu, X. F. Zhu, Z. W. Li, and H. Xu (2006). "The development of special drills for high-efficient drilling austenitic stainless steel part II: Coating selection and experiment research." *Key Engineering Materials*, Vol. 315-316, pp. 200-204.
- Chen, M., G. Liu, and X. H. Zhang (2007). "Optimization studies on hole-making tools for high-performance cutting austenitic stainless steel." *Machining Science and Technology*, Vol. 11, No. 2, pp. 183-200.

Churi, N. J., Z. C. Li, Z. J. Pei, and C. Treadwell (2005). "Rotary ultrasonic machining of titanium alloy: a feasibility study." *Proceedings of IMECE*, Orlando, FL, Vol. 16-2, pp. 885-892.

Churi, N. J., Z. J. Pei, and C. Treadwell (2007). "Wheel wear mechanisms in rotary ultrasonic machining of titanium." *Proceedings of IMECE*, Seattle, WA, Vol. 3, pp. 399-407.

Churi, N. J., Z. J. Pei, and C. Treadwell (2006). "Rotary ultrasonic machining of titanium alloy: effects of machining variables." *Machining Science and Technology*, Vol. 10, No. 3, pp. 301-321.

Churi, N. J., Z. J. Pei, and C. Treadwell (2007). "Rotary ultrasonic machining of titanium alloy (ti-6Al-4V): effects of tool variables." *International Journal of Precision Technology*, Vol. 1, No. 1, pp. 85-96.

Churi, N. J., Z. J. Pei, C. Treadwell, and D. Shorter (2007). "Rotary ultrasonic machining of silicon carbide: designed experiments." *International Journal of Manufacturing Technology and Management*, Vol. 12, No. 1-3, pp. 284-287.

Deng, G. P., S. Z. Li, S. Q. Wu, and X. G. Yang (1993). "Ultrasonic vibration drilling of small-diameter deep holes of difficult-to-machine stainless steel: Theoretical analysis and comparative experimental research." *Manufacturing Science and Engineering*, Vol. 63, pp. 835-839.

Hu, P., J. M. Zhang, Y. Jiao, Z. J. Pei, and C. Treadwell (2003). "Experimental investigation on coolant effects in rotary ultrasonic machining." *Proceedings of the NSF Workshop on Research Needs in Thermal Aspects of Material Removal Processes*, Stillwater, OK, June 10-12, pp. 340-345.

Jiao, Y., P. Hu, Z. J. Pei, and C. Treadwell (2005). "Rotary ultrasonic machining of ceramics: design of experiments." *International Journal of Manufacturing Technology and Management*, Vol. 7, No. 2-4, pp. 192-206.

Jiao, Y., W. J. Liu, Z. J. Pei, X. J. Xin, and C. Treadwell (2005). "Study on edge chipping in rotary ultrasonic machining on ceramics: an integration of designed experiment and FEM analysis." *Journal of Manufacturing Science and Engineering*, Vol. 127, No. 4, pp. 752-758.

Jing, L. L., Z. Y. Li, M. Chen, F. H. Sun, Z. G. Hu, X. F. Zhu, Z. W. Li, and H. Xu (2005). "Experimental study on the cutting deformation in drilling austenitic stainless steel." *Journal of Shanghai Jiaotong University*, Vol. 39, No. 11, pp. 1746-1750.

Khanna, N., Z. J. Pei, and P. M. Ferreira (1995). "An experimental investigation of rotary ultrasonic grinding of ceramic disks." *Technical Papers of NAMRI/SME*, pp. 67-72.

Li, Z. C., Y. Jiao, T. W. Deines, Z. J. Pei, and C. Treadwell (2004). "Experimental study on rotary ultrasonic machining (RUM) of poly crystalline diamond compacts (PDC)." Proceedings of IIE Annual Conference and Exhibition, Houston, TX, May 15-19.

Li, Z. C., Y. Jiao, T. W. Deines, Z. J. Pei, and C. Treadwell (2005). "Development of an innovative coolant system for rotary ultrasonic machining." *International Journal of Manufacturing Technology and Management*, Vol. 7, No. 2-4, pp. 318-328.

Li, Z. C., Y. Jiao, T. W. Deines, Z. J. Pei, and C. Treadwell (2005). "Rotary ultrasonic machining of ceramic matrix composites: Feasibility study and designed experiments." *International Journal of Machine Tools and Manufacture*, Vol. 45, No. 12-13, pp. 1402-1411.

Li, Z. C., Z. J. Pei, W. M. Zeng, P. Kwon, and C. Treadwell (2005). "Preliminary experimental study of rotary ultrasonic machining on zirconia toughened alumina." *Transactions of NAMRI/SME*, Vol. 33, pp. 89-96.

Li, Z. C., Z. J. Pei, T. Sisco, A. C. Micale, and C. Treadwell (2007). "Experimental study on rotary ultrasonic machining of graphite/epoxy panel." *Proceedings of the ASPE Spring Topical Meeting on Vibration Assisted Machining Technology*, Chapel Hill, NC, April 16-17, pp. 52–57.

Liu, G., M. Chen, L. L. Jing, Z. G. Hu, X. F. Zhu, Z. W. Li, and H. Xu (2006). "The development of special drills for high-efficient drilling austenitic stainless steel - part I: drill comparison and experiment research." *Key Engineering Materials*, Vol. 315-316, pp. 195-199.

Margolis, D. (2006). "Dude, where's my tool? [modular drawer storage system]." *Cutting tool Engineering*, Vol. 58, No. 9, pp. 66-71.

Ng, G. K. L., and L. Li (2003). "Repeatability characteristics of laser percussion drilling of stainless-steel sheets." *Optics and Lasers in Engineering*, Vol. 39, No. 1, pp. 25-33.

Pei, Z. J., P. M. Ferreira, and M. Haselkorn (1995). "Plastic flow in rotary ultrasonic machining of ceramics." *Journal of Materials Processing Technology*, Vol. 48, No. 1-4, pp. 771-777.

Pei, Z. J., P. M. Ferreira, S. G. Kapoor, and M. Haselkorn (1995). "Rotary ultrasonic machining for face milling of ceramics." *International Journal of Machine Tools and Manufacture*, Vol. 35, No. 7, pp. 1033-1046.

Pei, Z. J., and P.M. Ferreira (1998). "Modeling of ductile mode material removal in rotary ultrasonic machining." *International Journal of Machine Tools and Manufacture*, Vol. 38, No. 10-11, pp. 1399-1418.

Pei, Z. J., and P.M. Ferreira (1999). "An experimental investigation of rotary ultrasonic face milling." *International Journal of Machine Tools and Manufacture*, Vol. 39, No. 8, pp. 1327-1344.

Prabhakar, D (1992). "Machining advanced ceramic materials using rotary ultrasonic machining process." University of Illinois at Urbana–Champaign, M.S. Thesis.

Treadwell, C., and Z. J. Pei (2003). "Machining ceramics with rotary ultrasonic machining." *Ceramic Industry*, No. June, pp. 39-42.

Tyrrell, W. R. (1970). "New method for machining hard and brittle materials." *SAMPE Quarterly*, Vol. 1, No. 2, pp. 55-59.

Tyrrell, W. R. (1970). "Rotary ultrasonic machining." *SME Technical Paper* MR70-516.

Ya, G., H. W. Qin, S. C. Yang, and Y. W. Xu (2002). "Analysis of the rotary ultrasonic machining mechanism." *Journal of Materials Processing Technology*, Vol. 129, No. 1-3, pp. 182-185.

Zeng, W. M., Z. C. Li, Z. J. Pei, and C. Treadwell (2004). "Experimental investigation into rotary ultrasonic machining of alumina." *Proceedings of IMECE*, Anaheim, CA, November 13-19.

Zeng, W. M., Z. C. Li, Z. J. Pei, and C. Treadwell (2005). "Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics." *International Journal of Machine Tools and Manufacture*, Vol. 45, No. 12-13, pp. 1468-1473.

Zhang, Q. H., C. L. Wu, J. L. Sun, and Z. X. Jia (2000). "Mechanism of material removal in ultrasonic drilling of engineering ceramics." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 214, No. 9, pp. 805-810.

Zhong, J. W., Y. P. Ma, F. H. Sun, and M. Chen (2004). "Research on high-speed drilling performances of austenitic stainless steels." *Journal of Shanghai Jiaotong University*, Vol. 38, pp. 83-88.

Chapter 8 - Aerospace Stainless Steel - Design of Experiment on Surface Roughness

Paper title:

Surface roughness in rotary ultrasonic machining of stainless steels

Published in:

Proceedings of the IIE Annual Conference and Expo 2009 – Innovations Revealed, May
30 – June 3, 2009, Miami, FL, USA.

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Van Vleet, E.¹, Wang, Q.G.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State
University, Manhattan, KS 66506, USA

2. Key Laboratory of the Ministry of Education for Precision and Non-traditional
Machining Technology, Dalian University of Technology, Dalian, Liaoning, China

Abstract

Stainless steels have a variety of engineering applications but are difficult to machine. Drilling is a commonly seen machining technique for stainless steels. Poor thermal conductivity and severe hardening of stainless steels tend to cause high temperature at drilling region and strong cutting force on cutting tools. As a result, drilling efficiency on stainless steels is usually low and lives of cutting tools are usually short. Therefore, more cost-effective drilling processes for stainless steels are desirable. Rotary ultrasonic machining (RUM) is one of the nontraditional drilling processes. It has been used to drill holes in ceramics, composites, titanium and its alloys. But it has never been used for stainless steels. This paper presents results on surface roughness in an experimental investigation into RUM of stainless steels. Three-variable two-level full factorial design is used for the experiments. Main effects as well as interaction effects of three process variables (spindle speed, feedrate, and ultrasonic power) on surface roughness are revealed. Other results of this investigation will be published in a separate paper.

Keywords: Design of experiment, Drilling, Machining, Rotary ultrasonic machining, Stainless steels, Surface roughness

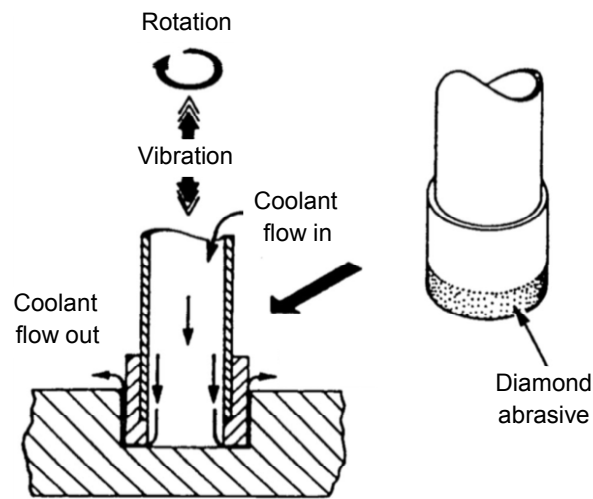
8.1 Introduction

Stainless steels have a variety of engineering applications, such as aerospace industry, chemical industry, and medical field. However, their machinability is poor because of their high toughness, low thermal conductivity, and large chip deformation. In production practice, machining of stainless steels tends to have problems of difficult chip removal, high cutting force, high temperature, short tool life, etc. [1-3].

Drilling comprises approximate 30% of all metal cutting operations [2]. Most drills used in drilling of stainless steels are made of high-speed steels with standard geometrical structure.

These standard twist drills often have the following problems: large thrust force, high drilling temperature, severe work-hardening, short tool life, and bad chip disposal. In many cases, they cannot meet requirement of high-efficient drilling for stainless steels [1-4]. It is desirable to develop more cost-effective drilling methods for stainless steels. Rotary ultrasonic machining (RUM) has been used to drill a variety of materials [5-10]. But it has never been used for stainless steels. Figure 8.1 illustrates the RUM process. The cutting tool is a core drill made of metal-bonded diamond abrasives. When machining, the rotating tool vibrates at ultrasonic frequencies and moves along its axial direction towards the workpiece. Meanwhile, coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill and keeps it cool.

Figure 8.1 Illustration of rotary ultrasonic machining.



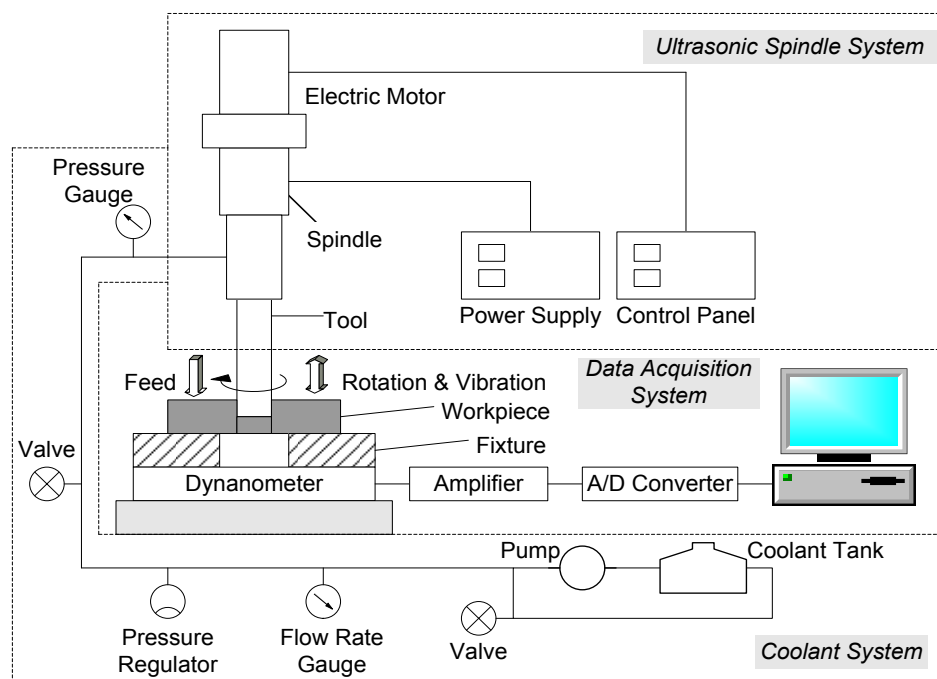
This paper presents results of an experimental investigation into RUM of stainless steels. Three-variable two-level full factorial design is used for the experiments. Main effects as well as interaction effects of three process variables (spindle speed, feedrate, and ultrasonic power) on

surface roughness are revealed. When appropriate, comparisons with results on RUM of other materials are also provided.

8.2 Experiment set-up and procedure

The machining experiments were performed on a Sonic-Mill Series 10 RUM machine (Sonic-Mill, Albuquerque, NM, USA). The experiment set-up is shown in Figure 8.2. A diamond core drill (NBR Diamond tool Corp., LaGrangeville, NY, USA) was used to drill the stainless steels workpiece. The outer and inner diameters of tool were 9.5 mm and 7.8 mm, respectively. The mesh size of the diamond abrasives was 80/100. Water-soluble Quakercool 6010 cutting fluid (Murdock Industrial Supply Co., Wichita, KS, USA) was used as coolant and diluted with water at a ratio of 1 to 14. The workpiece material was 15-5 stainless steels. The size of workpiece was $150 \times 125 \times 12.7$ mm.

Figure 8.2 Experiment set-up.



A 2^3 (two-level three-factor) full factorial design was employed. There were eight unique experiment conditions. Under each condition, the test was repeated once. The total number of tests was 16. Based on the experience from preliminary experiments and due to limitations of the experiment set-up, the experiments were focused on the study of the following three process variables:

- Spindle speed: rotational speed of cutting tool
- Feedrate: feedrate of cutting tool
- Ultrasonic power: percentage of power from ultrasonic power supply, which controls the ultrasonic vibration amplitude

Table 8.1 shows these variables and the values of the corresponding high and low levels.

Table 8.1 Low and high levels of process variables.

Process variable	Unit	Low level (–)	High level (+)
Spindle speed	rpm	2500	3500
Feedrate	mm/s	0.01	0.02
Ultrasonic power	%	20	35

Since RUM is a core drilling process, a hole and a rod will be produced after each test. Surface roughness was measured on the cylindrical surfaces of machined holes along the feed direction. A surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan) was used with the test range being set as 4 mm. The surface roughness in this study was characterized by R_a , average surface roughness. As shown in Figure 8.3, roughness was measured at two locations along the axial direction of the hole: entrance and exit. At each location, four measurements were performed with 90 degree between two adjacent measurements. Each

measurement was repeated twice. Therefore, for each test, eight Ra values were obtained. The Ra value for each test reported in Table 8.2 was the average of these eight Ra values.

Figure 8.3 Measurement procedure for surface roughness.

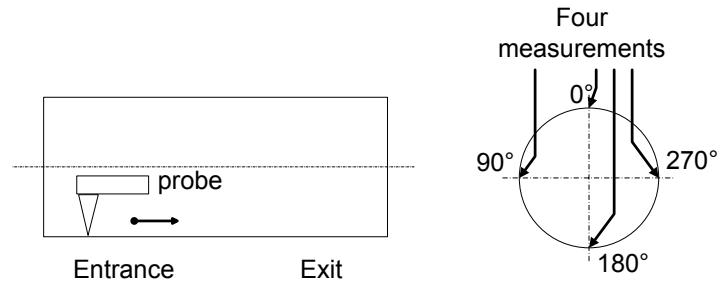


Table 8.2 Experiment matrix and results.

Spindle speed	Feedrate	Ultrasonic power	Surface roughness (μm)			
			Entrance		Exit	
			Test 1	Test 2	Test 1	Test 2
—	—	—	0.743	0.760	0.748	0.613
+	—	—	0.451	0.400	1.045	0.855
—	—	+	0.419	0.393	0.526	0.343
+	—	+	0.504	0.219	0.428	0.466
—	+	—	0.705	0.778	2.674	2.748
+	+	—	0.323	0.319	0.264	0.260
—	+	+	0.316	0.221	0.354	0.364
+	+	+	0.825	0.739	0.734	0.694

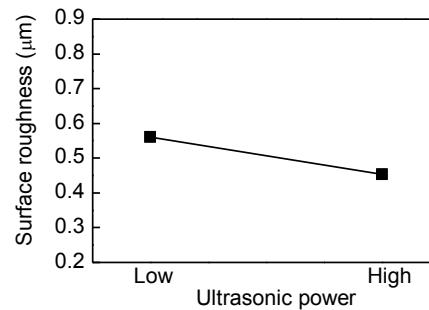
8.3 Results and discussion

The software, DESIGN EXPERT (version 5.0, Stat-Ease Corporation, Minneapolis, MN, USA) was used to analyze the data. The software can perform ANOVA (analysis of variance) to identify the significant effects. Geometric representations of the significant effects at the significance level of $\alpha = 0.05$ are presented in this paper with discussions.

8.3.1 Main effects on surface roughness at the entrance

Figure 8.4 shows the main effect of ultrasonic power on surface roughness at the entrance with P-value = 0.03. It can be seen that surface roughness decreases as ultrasonic power increases. Effects of spindle speed (P-value = 0.13) and feedrate (P-value = 0.33) are not significant at the significant level of $\alpha = 0.05$.

Figure 8.4 Main effect on surface roughness at the entrance.



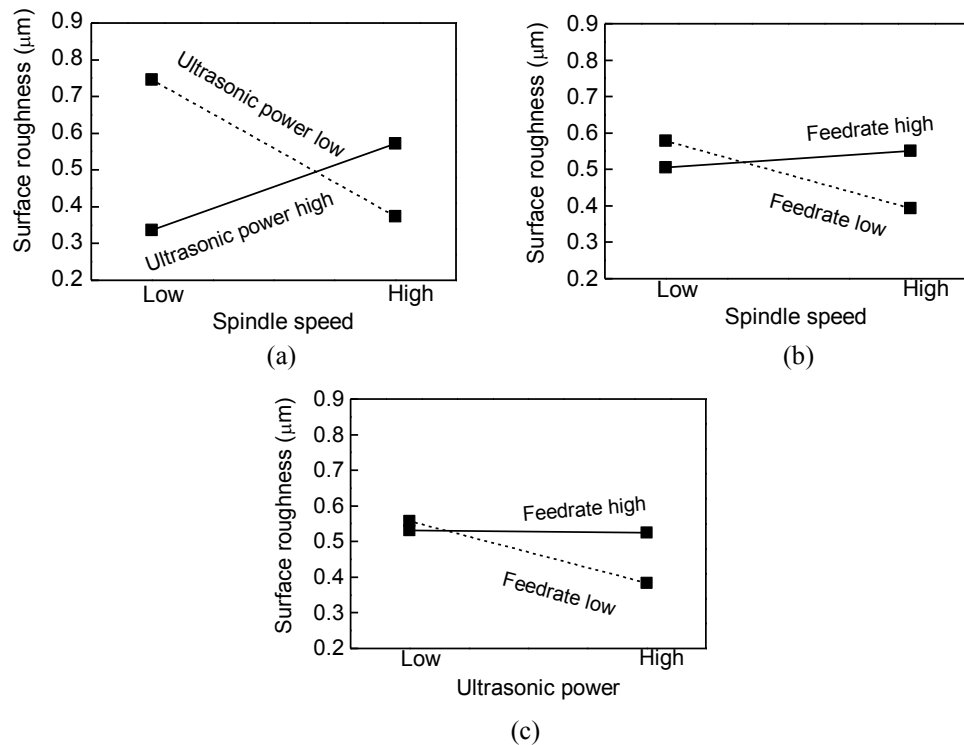
8.3.2 Two-factor interactions on surface roughness at the entrance

Three two-factor interaction effects can be obtained by the three-factor two-level factorial design. All three Two-factor interactions have significant effects on surface roughness at the entrance.

The interaction between spindle speed and ultrasonic power is the most significant with P-value < 0.00001. From Figure 8.5(a), it can be seen that, with increase of spindle speed, surface roughness decreases at the low level of ultrasonic power but increases at the high level of ultrasonic power. The interaction between spindle speed and feedrate (P-value = 0.02) is shown in Figure 8.5(b). With increase of spindle speed, surface roughness decreases at the low level of feedrate but increases at the high level of feedrate. The interaction between ultrasonic power and

feedrate (P-value = 0.04) is shown in Figure 8.5(c). With increase of ultrasonic power, surface roughness decreases at the low level of feedrate but stays nearly unchanged at the high level of feedrate.

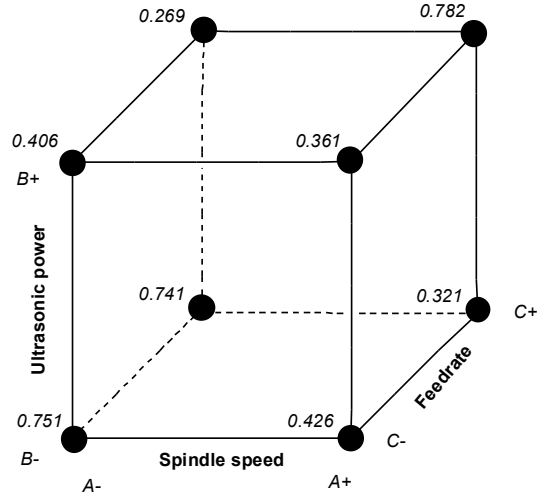
Figure 8.5 Two-factor interactions on surface roughness at the entrance.



8.3.3 Three-factor interactions on surface roughness at the entrance

The three-factor interaction (P-value = 0.004) of spindle speed, ultrasonic power, and feedrate on surface roughness, as shown in Figure 8.6, is significant. The combination (when the surface roughness is the lowest) is low spindle speed, high feedrate, and high ultrasonic power.

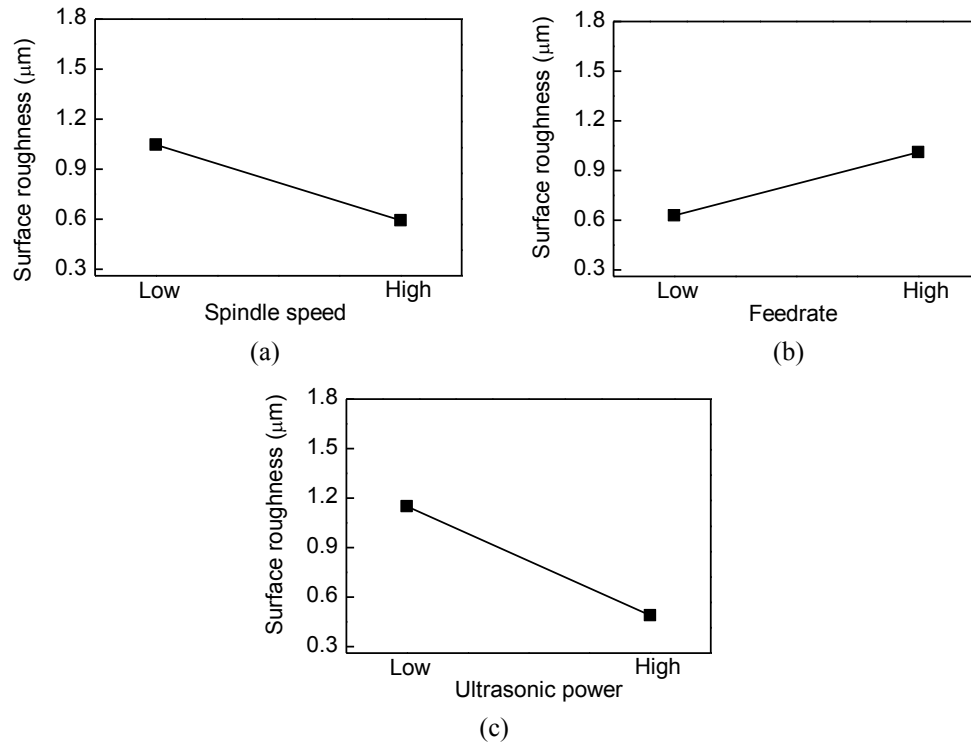
Figure 8.6 Three-factor interactions on surface roughness at the entrance.



8.3.4 Main effects on surface roughness at the exit

Main effects of three process variables (spindle speed, feedrate, and ultrasonic power) on surface roughness at the exit are presented in Figure 8.7. Since P-values of all these three effects are less than 0.00001, they are all significant. These plots show that surface roughness at the exit decreases with increase of spindle speed and ultrasonic power, and with decrease of feedrate.

Figure 8.7 Main effects on surface roughness at exit location.



8.3.5 Two-factor interactions on surface roughness at the exit

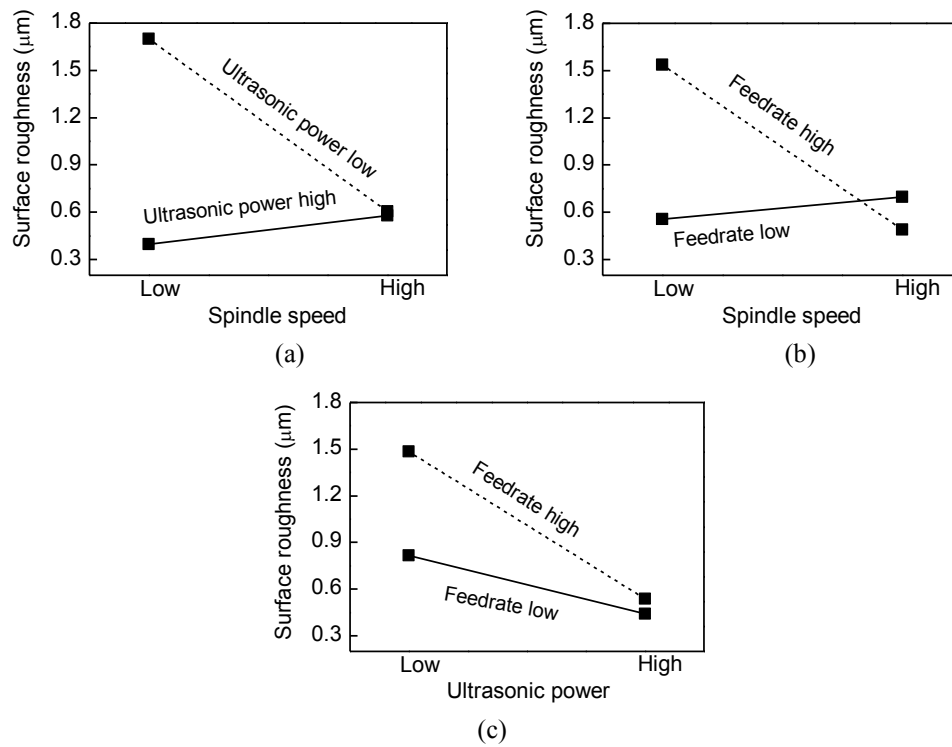
The results are plotted in Figure 8.8. All these three interactions have significant effects. Figure 8.8(a) shows the interaction between spindle speed and ultrasonic power (P-value < 0.00001). It can be seen that, with increase of spindle speed, surface roughness increases at the high level of ultrasonic power but decreases at the low level of ultrasonic power.

The interaction between spindle speed and feedrate (P-value < 0.00001) is shown in Figure 8.8(b). With increase of spindle speed, surface roughness decreases at the high level of feedrate but increases at the low level of feedrate.

The interaction between ultrasonic power and feedrate (P-value < 0.00001) is shown in Figure 8.8(c). It can be seen that, with the increase of ultrasonic power, surface roughness

decreases at both high and low levels of feedrate but with different slopes. The decreasing slope of surface roughness at the high level of feedrate is larger than that at the low level of feedrate.

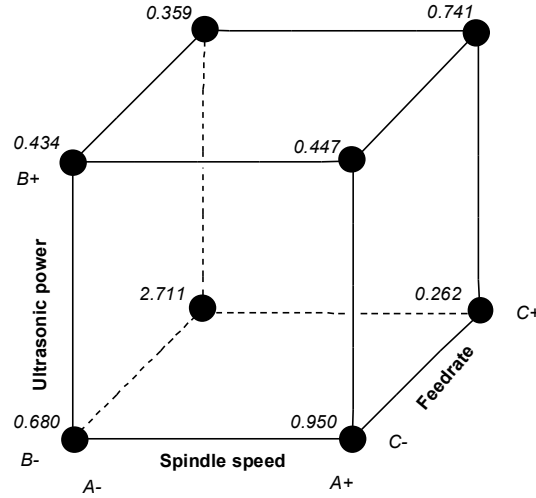
Figure 8.8 Two-factor interactions on surface roughness at the exit.



8.3.6 Three-factor interactions on surface roughness at the exit

The three-factor interaction ($P\text{-value} < 0.00001$) of spindle speed, ultrasonic power, and feedrate on surface roughness, as shown in Figure 8.9, is significant. The combination (when surface roughness is the lowest) is high spindle speed, high feedrate, and low ultrasonic power.

Figure 8.9 Three-factor interactions on surface roughness at the exit.



8.4 Conclusions

In the present paper, rotary ultrasonic machining (RUM) using a diamond tool was introduced into drilling stainless steels for the first time. 2^3 (two-level, three-factor) full factorial design was employed to study the relationships between surface roughness and three process variables (spindle speed, feedrate, and ultrasonic power). This paper reports main effects, two-factor interactions, and three-factor interactions of these three process variables.

The following conclusions are drawn from this study:

- (a) At the entrance, only ultrasonic power has significant effects on surface roughness. Higher ultrasonic power leads to lower surface roughness. All two-factor and three-factor interactions have significant effects on surface roughness.
- (b) At the exit, spindle speed, feedrate, and ultrasonic power all have significant effects. Higher spindle speed, lower feedrate, and higher ultrasonic power lead to a lower surface roughness. All two-factor and three-factor interactions have significant effects on surface roughness.

- (c) Surface roughness at the entrance is always lower than that at the exit.

Conclusions (a) and (b) are consistent with some trends reported in the literature on RUM of other materials (such as ceramics and titanium), but different from other trends reported. Detailed comparisons and discussion are not provided in this paper due to the page limit.

Conclusion (c) is the first in the literature. There have been no reports in the literature on surface roughness on both entrance and exit of holes drilled by RUM. However, similar trends were observed when RUM of titanium and KDP crystal in the authors' group. Hypotheses have been developed to explain this observed trend. Experiments will be conducted to test these hypotheses. Results will be reported later.

Acknowledgements

The authors would like to thank Mr. Bruno Renzi at NBR Diamond Tool Corporation for providing the diamond tool, Mr. Clyde Treadwell at Sonic-Mill for providing technical assistance on RUM machine, and Mr. Timothy Denies at Kansas State University for providing technical assistance in fabricating the fixture and setting up the RUM machine.

References

- [1] Li, X.K., Chen, Z.B., Chen, M., Hu, Z.G., Zhu, X.F., and Li, Z.W., 2006, "Research on Wear Mechanism of Coated HSS Drills During Machining Stainless Steel," *China Mechanical Engineering*, 17(4), 354-61. (in Chinses)
- [2] Dolinsek, S., 2003, "Work-Hardening in the Drilling of Austenitic Stainless Steels," *Journal of Materials Processing Technology*, 133(1-2), 63-70
- [3] Sun, Y., 1999, "Kinematics-Driven Modeling and Grinding Path Generation for Drill Geometry," Ph.D. Dissertation, The University of Michigan.

- [4] Kosmol, J., Czech, M., Klarecki, K., and Sliwka, J., 1999, "Optimizations of Drills For The Machining of Austenitic Steel," *Journal of Materials Processing Technology*, 89-90(May), 117-122.
- [5] Churi, N. J., Li, Z. C., Pei, Z. J., and Treadwell, C., 2005, "Rotary Ultrasonic Machining of Titanium Alloy: A Feasibility Study," *Proceedings of IMECE*, November 5-11, Orlando, FL, 885-892.
- [6] Churi, N. J., Pei, Z. J., and Treadwell, C., 2006, "Rotary Ultrasonic Machining of Titanium Alloy: Effects of Machining Variables," *Machining Science and Technology*, 10(3), 301-321.
- [7] Churi, N. J., Pei, Z. J., and Treadwell, C., 2007, "Wheel Wear Mechanisms in Rotary Ultrasonic Machining of Titanium," *Proceedings of IMECE*, November 11-15, Seattle, WA, 399-405.
- [8] Churi, N. J., Pei, Z. J., and Treadwell, C., 2007, "Rotary Ultrasonic Machining of Titanium Alloy (Ti-6Al-4V): Effects of Tool Variables," *International Journal of Precision Technology*, 1(1), 85-96.
- [9] Churi, N. J., Pei, Z. J., and Treadwell, C., and Shorter, D., 2007, "Rotary Ultrasonic Machining of Silicon Carbide: Designed Experiments," *International Journal of Manufacturing Technology and Management*, 12(1-3), 284-287.
- [10] Jiao, Y., Hu, P., Pei, Z. J., and Treadwell, C., 2005, "Rotary Ultrasonic Machining of Ceramics: Design of Experiments," *International Journal of Manufacturing Technology and Management*, 7(2-4), 192-206.

Chapter 9 - Aerospace Stainless Steel - Hypotheses about Surface Roughness

Paper title:

Surface roughness in rotary ultrasonic machining: hypotheses and their testing via experiments and simulations

Submitted to:

International Journal of Manufacturing Research

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Deines, T.W.¹, Zhang, P.F.¹, and Treadwell, C.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

2. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Rotary ultrasonic machining (RUM) is a nontraditional drilling process. It has been used to drill not only brittle but also ductile materials. It was observed that the surface roughness of the drilled hole near the entrance side was better than that near the exit side. However, explanations about this observation could not be found in the literature. This paper aims to provide explanations about this observation. It presents three hypotheses and their testing via experiments and simulations.

Keywords: Grinding, Hypothesis, Machining, Rotary ultrasonic machining, Stainless steel, Surface roughness.

9.1 Introduction

Rotary ultrasonic machining (RUM) is a nontraditional machining method and has been used to drill a variety of materials. It has been shown that RUM can effectively drill ceramics (Churi et al., 2007c; 2009; Jiao et al., 2005; Prabhakar, 1992; Zeng et al., 2004), composites (Li et al., 2004; 2005ab; 2007; Cong et al., 2011), titanium (Churi et al., 2005; 2006; 2007ab), and stainless steel (Cong et al., 2009ab; 2010). Figure 9.1 illustrates RUM. A rotating core drill (as illustrated in Figure 9.2) with metal-bonded diamond abrasives vibrates in the axial direction at an ultrasonic frequency and feeds towards the workpiece at a constant feedrate or pressure. Coolant is pumped through the core of the drill and washes away the swarf and keeps the tool cool.

Figure 9.1 Illustration of RUM.

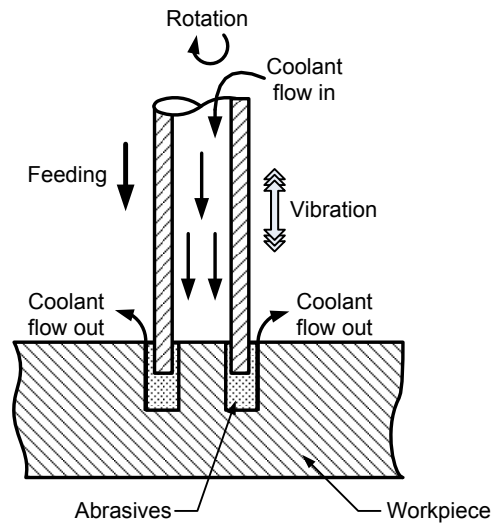
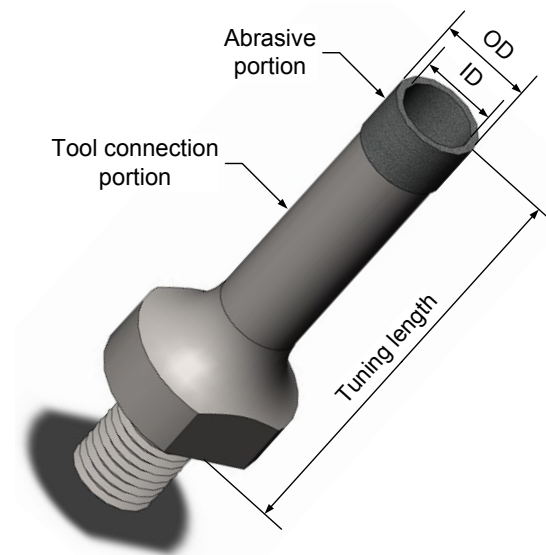


Figure 9.2 Illustration of the core drill.



Effects of input variables (tool rotation speed; feedrate or constant pressure; ultrasonic vibration amplitude and frequency; diamond type, grit size, and concentration; and bond type for the tool) on surface roughness in RUM of brittle materials (including several types of ceramics) were investigated experimentally (Churi et al., 2007c; 2009; Jiao et al., 2005; Prabhakar, 1992; Zeng et al., 2004). Experimentally-determined relationships between input variables (e.g., tool rotation speed, feedrate, and ultrasonic power) and surface roughness in RUM of ductile

materials (titanium and stainless steel) were also reported (Churi et al., 2005; 2006; 2007ab; Cong et al., 2009b; 2010). In addition, it was observed (Cong et al., 2010) when using RUM to drill stainless steel that surface roughness of the machined hole and rod near the entrance side was better than that near the exit side. Figure 9.3 illustrates the entrance side and exit side of the machined hole and rod. Figure 9.4 shows pictures of machined surfaces at these two locations (near the entrance side and near the exit side). However, explanations about this observation could not be found in the literature. This paper aims to provide explanations about this observation. Such knowledge is important in order to further improve the surface roughness of holes machined by RUM.

This paper presents three hypotheses on why surface roughness near the entrance side is better than that near the exit side, and their testing via experiments and simulations. It is organized in five sections. Each of the next three sections presents one hypothesis and its testing. The last section contains conclusions.

Figure 9.3 Illustration of entrance and exit sides of machined hole and rod.

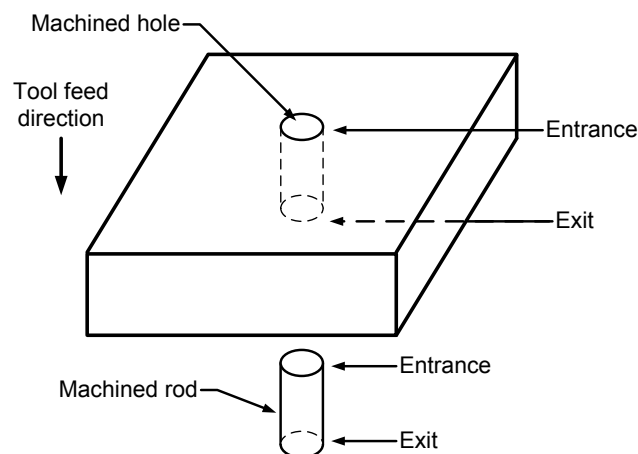
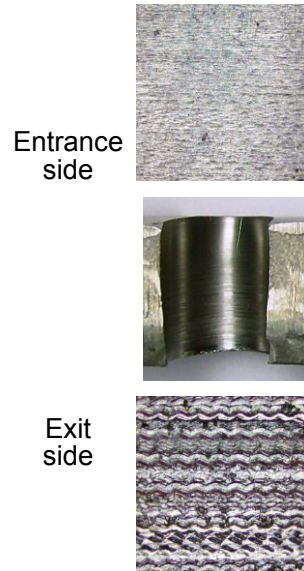


Figure 9.4 Pictures of machined hole surface by RUM.



9.2 Hypothesis 1

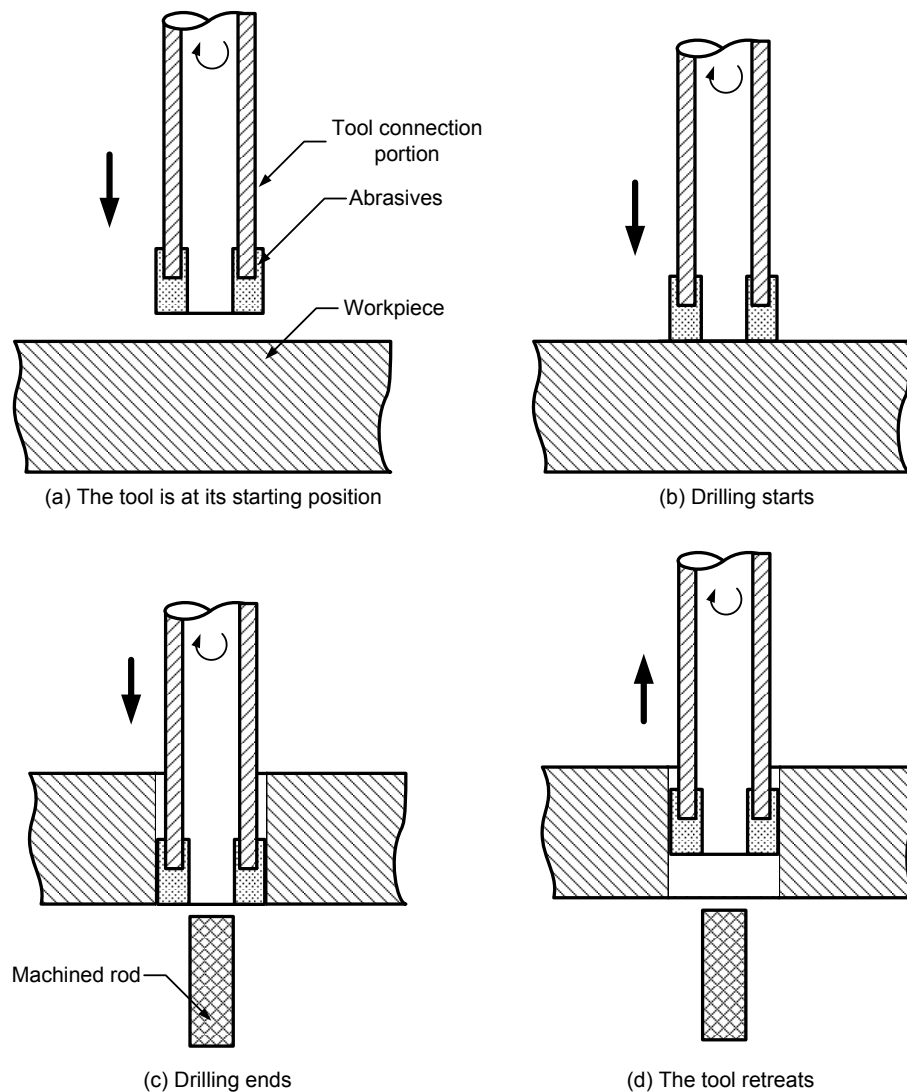
9.2.1 Hypothesis

Figure 9.5 shows the four stages of RUM drilling:

- (a) The tool is at its starting position;
- (b) Drilling starts, the vibrating tool (a core drill with diamond abrasives) is fed into the workpiece;
- (c) Drilling ends;
- (d) The tool retreats.

After the tool finishes drilling the hole, it retreats to its starting position. As it retreats, the tool still rotates and vibrates, and may grind the wall of the machined hole. The hole surface near the entrance side might be ground again while the tool retreats but the hole surface near the exit side might not. It is hypothesized that this additional grinding is the cause for the difference in surface roughness at the two locations.

Figure 9.5 Illustration of Hypothesis 1.



9.2.2 Hypothesis testing via experiments

9.2.2.1 Experiment set-up

The experiments were performed on a Sonic-Mill Series 10 RUM machine (Sonic-Mill, Albuquerque, NM, USA). The experiment set-up is shown in Figure 9.6. The diamond core drills were provided by NBR Diamond tool Corp. (LaGrangeville, NY, USA). The tuning length of these drills was 45.7 mm. Each drill had a connection portion and an abrasive portion. For the

abrasive portion, the outer diameter (OD) was 9.59 mm and the inner diameter (ID) was 7.80 mm. The mesh size of the diamond abrasives was 80/100. The bond type C (with harder bond material than bond type B) was used. The cutting fluid used was water-soluble Quakercool 6010 (Murdock Industrial Supply Co., Wichita, KS, USA). It was diluted with water at a ratio of 1 to 14. Other experiment conditions are shown in Table 9.1. Under each machining conditions, three holes were drilled.

Figure 9.6 Experiment set-up.

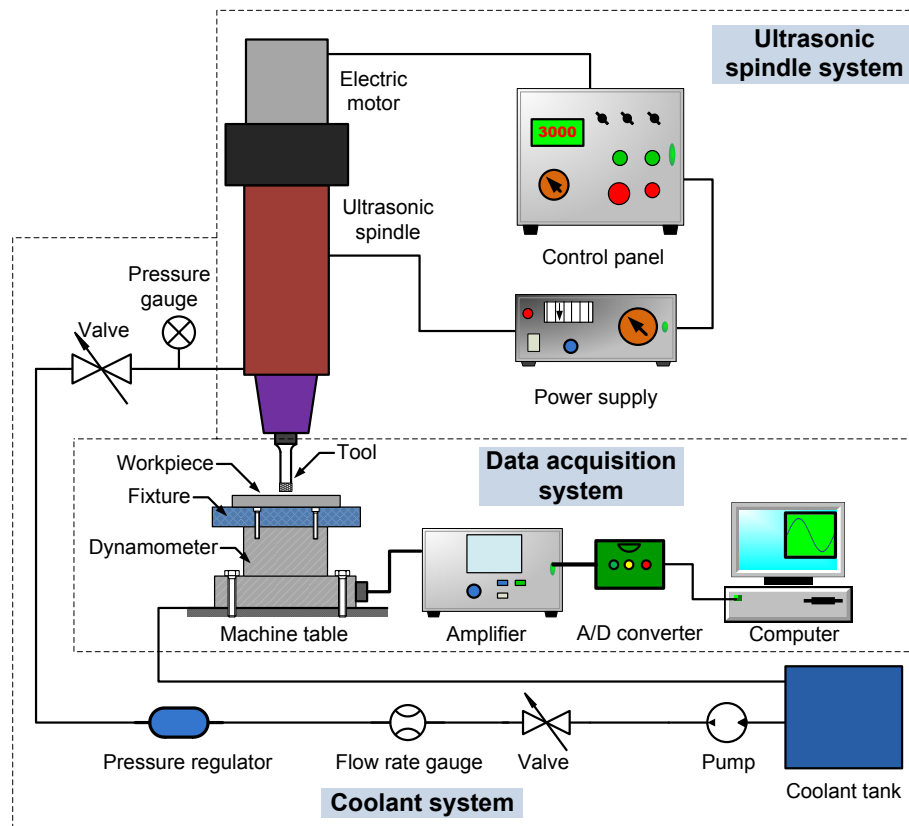


Table 9.1 Experiment conditions.

Variable	Value
Tool rotation speed (rpm)	3000
Feedrate (mm/s)	0.015
Ultrasonic power (%)	30

The surface roughness in this study was characterized by Ra, average surface roughness. It was measured with a surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan). The test range was set at 4 mm and cut-off length was set at 0.8 mm. Surface roughness was measured at two locations of the hole, near the entrance side and near the exit side. At each location, four measurements were performed with 90 degrees between two adjacent measurements. Each measurement was repeated twice. The reported Ra value for each location was the average of these eight collected data.

The workpiece material was stainless steel (15-5). Its prosperities are listed in Table 9.2. The workpiece size was 152 mm × 127 mm × 12.7 mm.

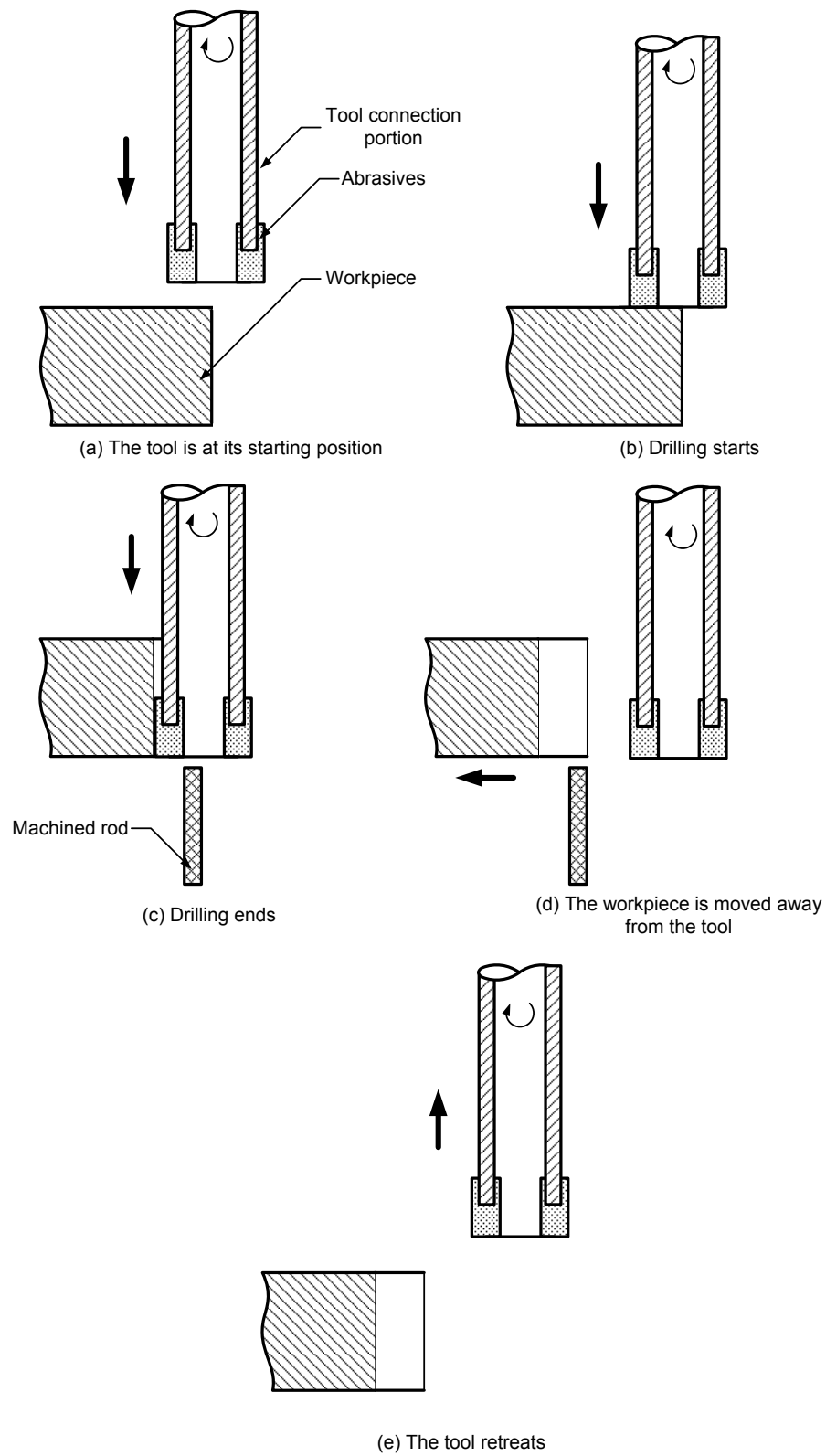
Table 9.2 Stainless steel properties.

Property	Value
Young's modulus (GPa)	200
Poisson's ratio	0.28
Yield strength (MPa)	1000 - 1100
Ultimate tensile strength (MPa)	1100 - 1200
Hardness, Rockwell (C)	35 - 40
Thermal conductivity (W/m·K)	20
Density (g/cm ³)	7.8

9.2.2.2 Experiment results from Test 1

Test 1 was designed to prevent the tool from grinding the hole surface near the entrance side while retreating. Only half of the hole (instead of a complete hole) was drilled so that the workpiece could be moved away from the tool after the tool drilled through the workpiece thickness. Figure 9.7 shows the five stages of this test.

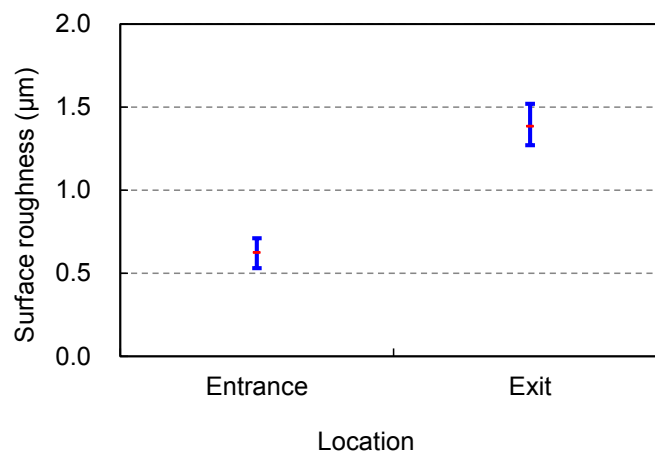
Figure 9.7 Illustration of Test 1 for Hypothesis 1.



- (a) The tool is at its starting position;
- (b) Drilling starts;
- (c) Drilling ends;
- (d) The workpiece is moved away from the tool;
- (e) The tool retreats to its starting position without touching the drilled half-hole surface.

If Hypothesis 1 is true, for the machined holes in this test, surface roughness at the two locations (near the entrance side and near the exit side) should be the same (or very similar). Figure 9.8 shows experiment results from this test. In Figure 9.8, error bars represent the maximum and minimum surface roughness values of the three holes drilled under each condition. The P-value from the t-test was 0.001. This means that, at the significance level of $\alpha = 0.001$, surface roughness near the entrance side was significantly better than that near the exit side. Therefore, Hypothesis 1 should be rejected.

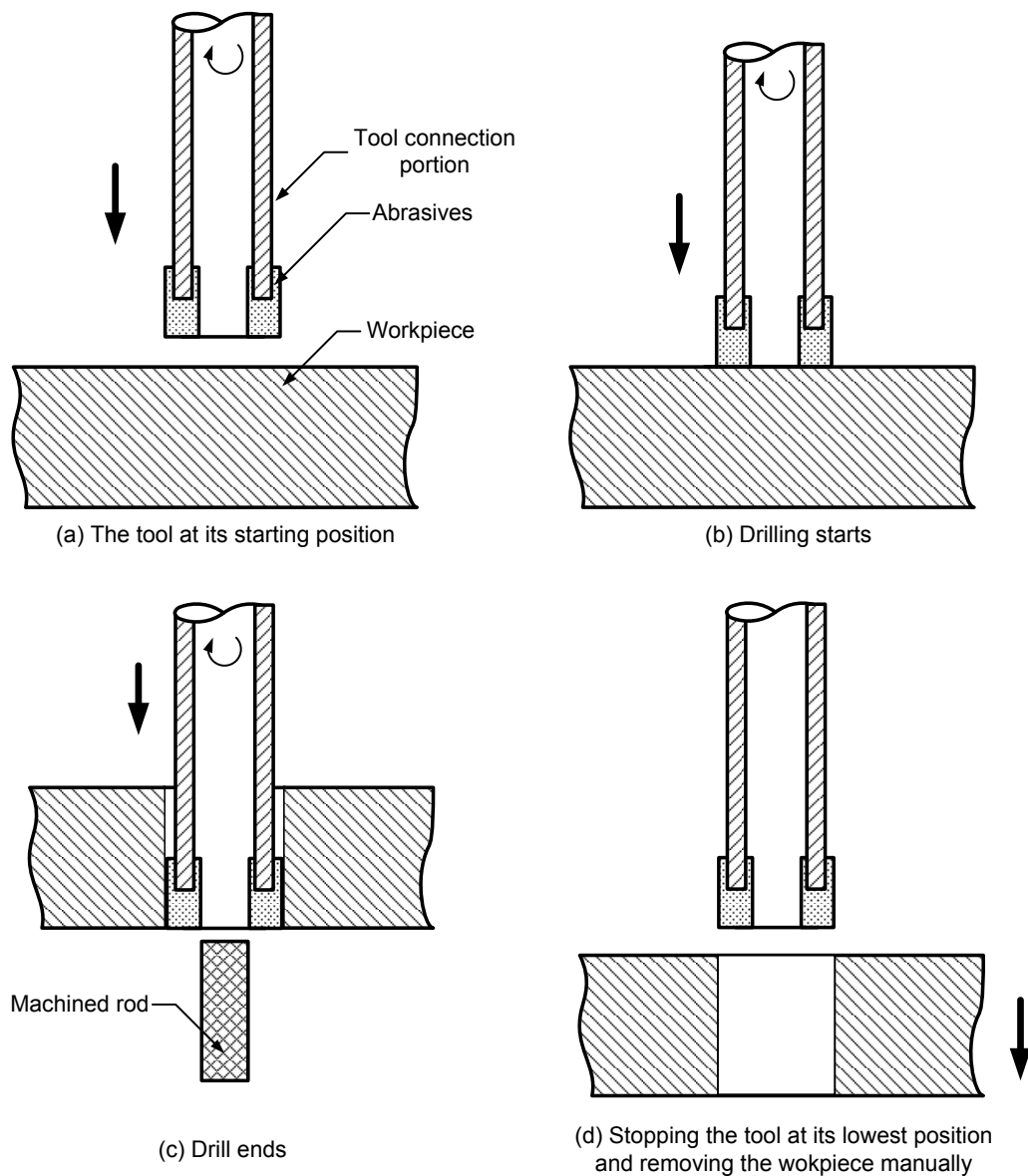
Figure 9.8 Experimental results of Test 1 for Hypothesis 1.



9.2.2.3 Experiment results from Test 2

Test 2 was also designed to prevent the tool from grinding the drilled hole near the entrance side when it retreats. This was achieved by stopping the tool at the lowest position and removing the workpiece manually. Figure 9.9 shows the four stages of this test.

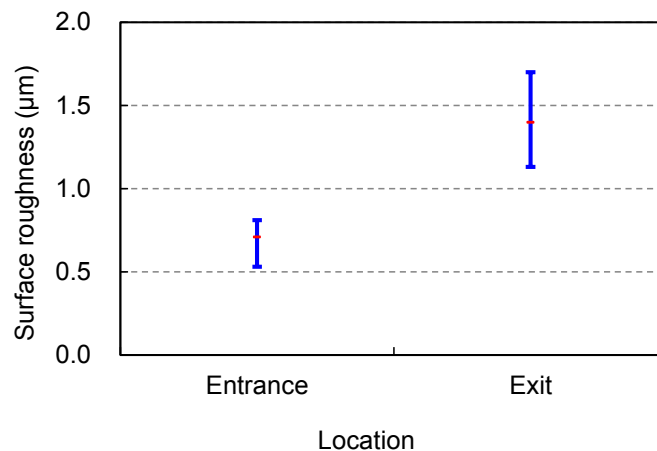
Figure 9.9 Illustration of Test 2 for Hypothesis 1.



- (a) The tool is at its starting position;
- (b) Drilling starts;
- (c) Drilling ends;
- (d) The tool stops at its lowest position and the workpiece is removed manually.

If Hypothesis 1 is true, for the machined holes in this test, surface roughness at the two locations (near the entrance side and near the exit side) should be approximately the same. Figure 9.10 shows the experiment results from this test. The P-value from the t-test was 0.002. This means that, surface roughness near the entrance side was significantly better than that near the exit side at the significance level of $\alpha = 0.002$. Therefore, Hypothesis 1 should be rejected.

Figure 9.10 Experimental results of Test 2 for Hypothesis 1.



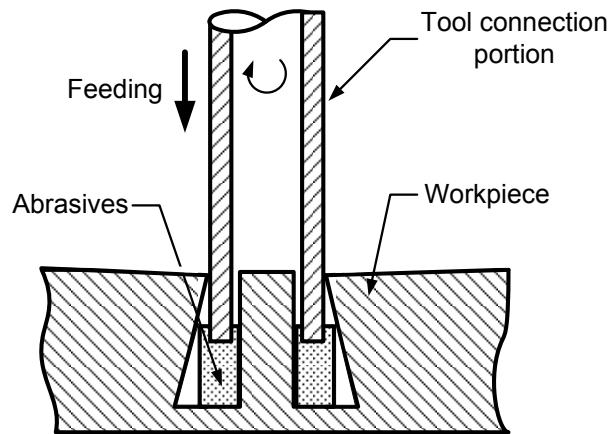
9.3 Hypothesis 2

9.3.1 Hypothesis

The workpiece may deform elastically under cutting force, causing the hole diameter near the entrance side become smaller than that near the exit side. If the deformation is large enough,

it is possible that the connection portion of the tool will rub the machined hole surface near the entrance side, as illustrated in Figure 9.11. It is hypothesized that the rubbing by the connection portion of the tool might improve the surface roughness near the entrance side.

Figure 9.11 Illustration of Hypothesis 2.



(The magnitude of deformation is greatly exaggerated for illustration purpose)

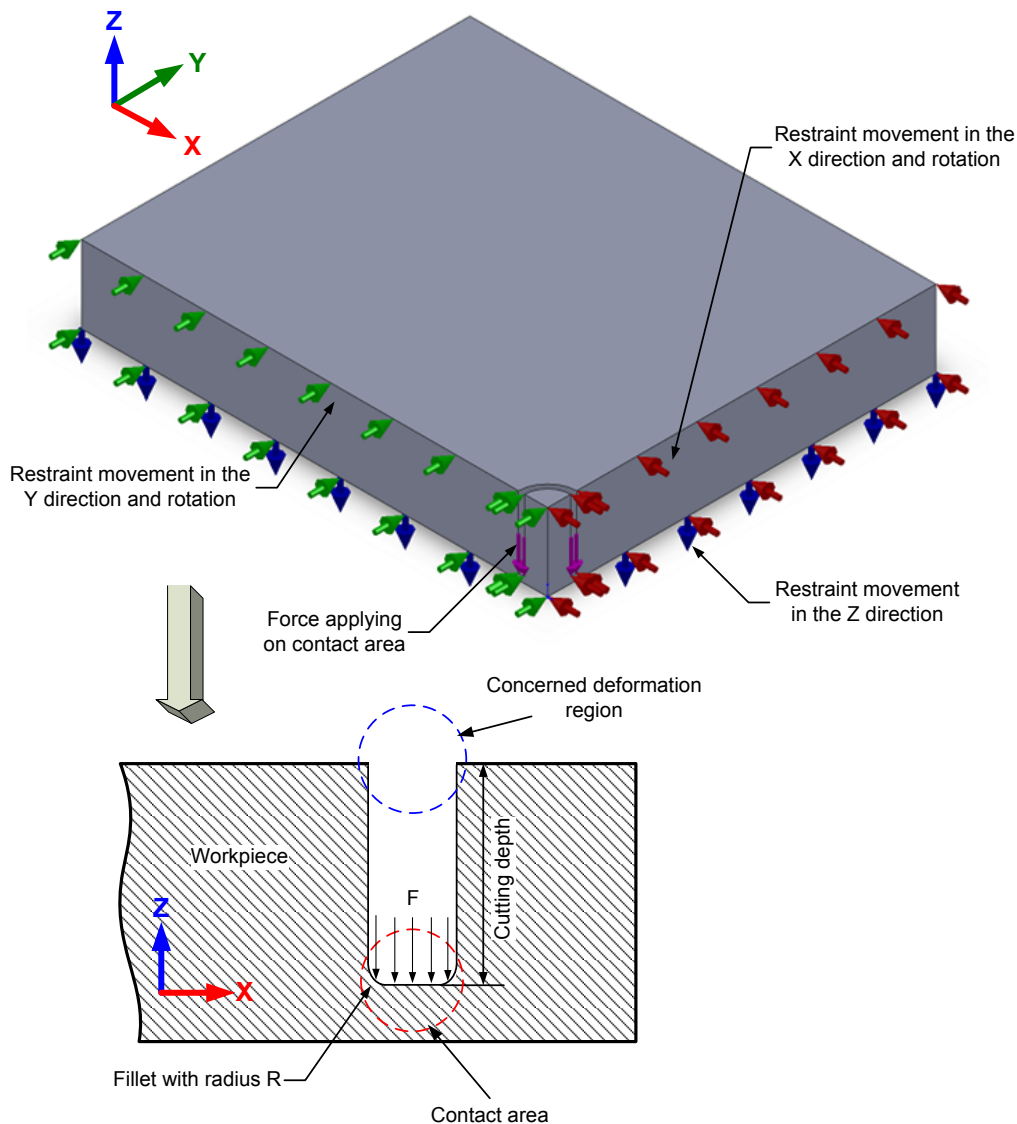
9.3.2 Hypothesis testing via simulations

9.3.2.1 Development of finite element analysis model

SolidWorks-simulation (SolidWorks Corp., Concord, MA, USA) was used to build a three-dimensional model (as shown in Figure 9.12) to simulate (calculate) the workpiece deformation during RUM drilling. The workpiece was modeled as a rectangle plate (152 mm $\times$ 127 mm $\times$ 12.7 mm) with a cylindrical recess that had an outer diameter (OD) of 9.59 mm and an inner diameter (ID) of 7.80 mm, the same as the OD and ID of the core drill. Due to the geometric symmetry of the workpiece, only 1/4 of the workpiece was modeled. If viewed on any X-Z cross-section (the X direction was the radial direction of the workpiece and the Z direction was parallel to the tool axial direction) through the workpiece center, the cylindrical recess

became a rectangular recess. Two corners of the rectangular recess were modeled as fillets with a radius of 0.05 mm. The fixture was a platform of a cuboid block with a center hole of 25.4 mm in diameter. The backside of the workpiece in contact with the fixture surface was constrained from moving in the vertical direction (the Z direction) by roller restraints. Two symmetry restraints were applied on the two clipping section surfaces. Sliding and rotation in the X and Y directions were also constrained.

Figure 9.12 Finite element analysis model of workpiece.



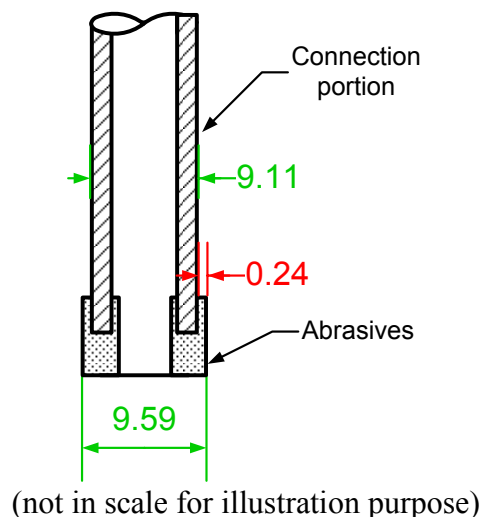
The cutting depth was the distance between the top surface of the workpiece and the bottom surface of the recess. The range of the cutting depth in the simulation was from 7 to 12 mm with 1 mm interval.

A maximum cutting force of 518 N (in the Z direction) was measured from previous experiments [Cong et al., 2008a]. This maximum force value was applied on the bottom of the rectangular recess.

9.3.2.2 Simulation results

Simulation results show that the maximum displacement (in the horizontal direction toward the hole center) of any point on the machined hole surface near the entrance was less than 10 μm . It is noted that the gap between the outer diameter of the connection portion of the tool and the outer diameter of the abrasive portion of the tool was 240 μm (as illustrated in Figure 9.13). In other words, the displacement was too small to allow the connection portion of the tool to rub the machined hole surface near the entrance side. Therefore, Hypothesis 2 should be rejected based on the simulation results.

Figure 9.13 Dimensions of the tools used in experiments (unit: mm).



9.4 Hypothesis 3

9.4.1 Hypothesis

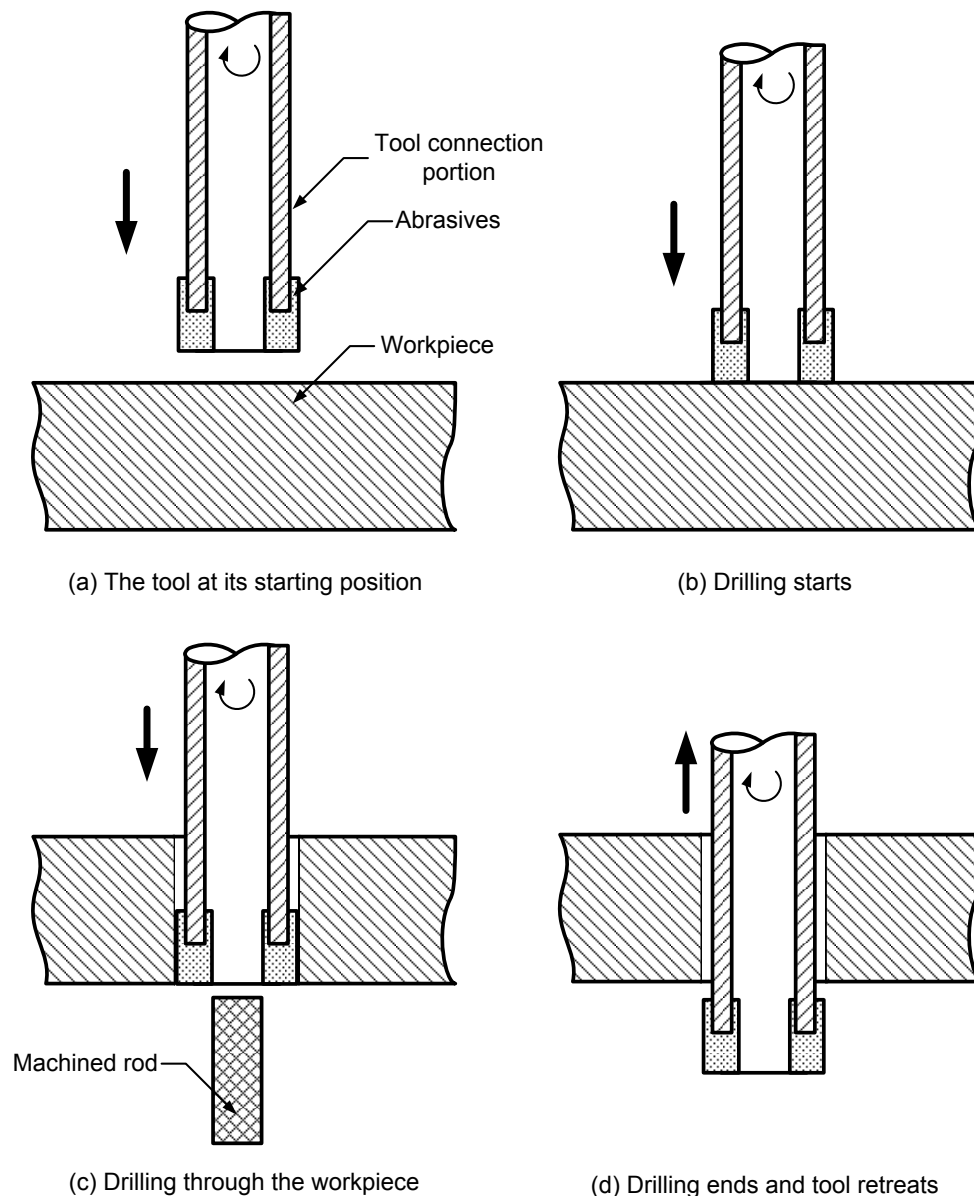
As illustrated in Figure 9.5, as soon as the tool drills through the workpiece thickness, the tool will retreat to its starting position. The location (on the machined hole surface) near the entrance side is ground by the full length of the abrasive portion of the tool, while the location near the exit side is ground by only a fraction of the length of the abrasive portion. It is hypothesized that the difference in the grinding duration by the abrasive portion of the tool causes the difference in surface roughness at the two locations.

9.4.2 Hypothesis testing via experiments

This test was designed to allow the entire abrasive portion of the tool to grind both locations (near the entrance side and near the exit side). It was done by feeding the tool until the entire abrasive portion went through the workpiece thickness, as illustrated in Figure 9.14. There are four stages in this test:

- (a) The tool is at its starting position;
- (b) Drilling starts;
- (c) The tool drills through the workpiece;
- (d) The tool retreats after the entire length of the abrasive portion passes through the exit side of the workpiece.

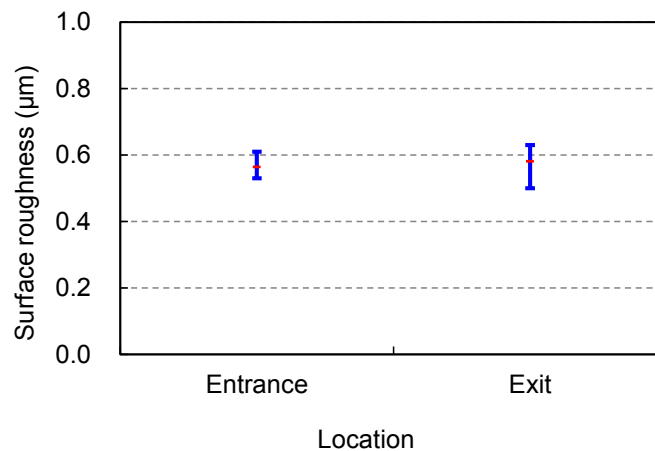
Figure 9.14 Illustration of Test for Hypothesis 3.



In this test, the entire abrasive portion of the tool could grind the entire length of the hole. Hence, the location near the exit side was ground for the same duration of time as the location near the entrance side. If Hypothesis 3 is true, for the holes drilled in this test, surface roughness values at the two locations (near the entrance side and near the exit side) should be approximately the same. As shown in Figure 9.15, experiment results are consistent with

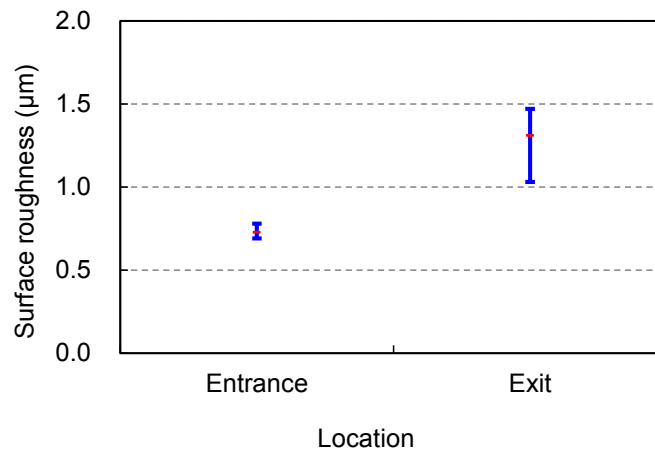
Hypothesis 3. The P-value from the t-test was 0.37. This means that, at the significance level of $\alpha = 0.37$, Hypothesis 3 cannot be rejected.

Figure 9.15 Experimental results of Test for Hypothesis 3.



As a reference, Figure 9.16 shows surface roughness results when drilling with RUM in the standard fashion (letting the tool retreat as soon as it cuts through the workpiece thickness). If Hypothesis 3 is true, surface roughness near the exit side on the holes drilled when letting the entire abrasive portion pass through the backside of the workpiece should be much improved over that on the holes drilled when letting the tool retreat as soon as it cuts through the workpiece thickness. This is confirmed by the experiment results (as shown in Figure 9.15 and Figure 9.16). The P-value from the t-test (to compare the roughness values near the exit side in Figure 9.15 and Figure 9.16) was 0.004. This means that, at the significance level of $\alpha = 0.004$, surface roughness near the exit side on the holes drilled when letting the entire abrasive portion pass through the backside of the workpiece (Figure 9.15) is significantly different from that on the holes drilled when letting the tool retreat as soon as it cuts through the workpiece thickness (Figure 9.16).

Figure 9.16 Surface roughness results when drilling with RUM in standard fashion.



9.5 Conclusions

Three hypotheses were proposed to explain why surface roughness of the drilled holes near the entrance side is better than that near the exit side in rotary ultrasonic machining. They were tested via experiments and finite element simulations using stainless steel as the example workpiece material.

Based on the results from the experiments and simulations, two hypotheses should be rejected but one cannot be rejected. Therefore, the reason for the difference in surface roughness is: The location near the entrance side was ground longer than the location near the exit side by the abrasive portion of the tool. The above results provide guidance for further improvement of surface roughness of drilled holes with rotary ultrasonic machining (as well as other drilling processes).

Acknowledgments

The work was supported by the National Science Foundation through Award CMMI-0900462. The authors would like to thank NBR Diamond Tool Corporation for providing the diamond tools.

References

- [1] Churi, N.J.; Li, Z.C.; Pei, Z.J.; Treadwell, C. (2005) Rotary ultrasonic machining of titanium alloy: a feasibility study. Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition, Orlando, FL, USA, November 5-11, 16-2: 885-892.
- [2] Churi, N.J.; Pei, Z.J.; Treadwell, C. (2006) Rotary ultrasonic machining of titanium alloy: effects of machining variables. *Machining Science and Technology*, 10: 301-321.
- [3] Churi, N.J.; Pei, Z.J.; Treadwell, C. (2007a) Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables. *International Journal of Precision Technology*, 1: 85-96.
- [4] Churi, N.J.; Pei, Z.J.; Treadwell, C. (2007b) Wheel wear mechanisms in rotary ultrasonic machining of titanium. Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition (ASME/IMECE), Seattle, WA, USA, November 11-15.
- [5] Churi, N.J.; Pei, Z.J.; Treadwell, C.; Shorter, D. (2007c) Rotary ultrasonic machining of silicon carbide: designed experiments. *International Journal of Manufacturing Technology and Management*, 12: 284-287.
- [6] Churi, N.J.; Pei, Z.J.; Treadwell, C.; Shorter, D. (2009) Rotary ultrasonic machining of dental ceramics. *International Journal of Machining and Machinability of Materials*, 6:

- 270-284.
- [7] Cong, W.L.; Pei, Z.J.; Churi, N.; Wang, Q.G. (2009a) Rotary ultrasonic machining of stainless steel: design of experiments. *Transactions of the North American Manufacturing Research Institution of SME*, 37: 261-268.
 - [8] Cong W.L.; Pei, Z.J.; Van Vleet, E.; and Wang, Q.G. (2009b) Surface roughness in rotary ultrasonic machining of stainless steels, Proceedings of the IIE Annual Conference and Expo 2009 – Innovations Revealed, Miami, FL,US, May 30 - June 3.
 - [9] Cong, W.L.; Pei, Z.J.; Deines, T.W.; Wang, Q.G. (2010) Rotary ultrasonic machining of stainless steels: empirical study of machining variables. *International Journal of Manufacturing Research*, 5: 370-386.
 - [10] Cong, W.L.; Feng, Q.; Pei, Z.J.; Deines, T.W.; Treadwell, C. (2011) Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables. Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference (MSEC), Corvallis, OR, June 13-17, 2011.
 - [11] Jiao, Y.; Hu, P.; Pei, Z.J.; Treadwell, C. (2005) Rotary ultrasonic machining of ceramics: design of experiments. *International Journal of Manufacturing Technology and Management*, 7: 192-206.
 - [12] Li, Z.C.; Jiao, Y.; Deines, T.W.; Pei, Z.J. Treadwell, C. (2004) Rotary ultrasonic machining (RUM) on ceramic matrix composites (CMC): designed experiments. Proceedings of the Fifth International Conference on High Temperature Ceramic Matrix Composites (HTCMC-5), Seattle, WA, US, September 12-16.
 - [13] Li, Z.C.; Jiao, Y.; Deines, T.W.; Pei, Z.J.; Treadwell, C. (2005a) Rotary Ultrasonic Machining of Ceramic Matrix Composites: Feasibility Study and Designed Experiments.

- International Journal of Machine Tools and Manufacture*, 45: 1402-1411.
- [14] Li, Z.C.; Pei, Z.J.; Zeng, W.M.; Kwon, P., Treadwell, C. (2005b) Preliminary experimental study of rotary ultrasonic machining on zirconia toughened alumina. *Transactions of the North American Manufacturing Research Institution of SME*, 33: 261-268.
- [15] Li, Z.C.; Pei, Z.J.; Sisco, T.; Micale, A.C.; Treadwell, C. (2007) Experimental study on rotary ultrasonic machining of graphite/epoxy panel. Proceedings of the ASPE 2007 Spring Topical Meeting on Vibration Assisted Machining Technology, Chapel Hill, NC, US, April 16-17, 52-57.
- [16] Prabhakar, D. (1992) *Machining Advanced Ceramic Materials Using Rotary Ultrasonic Machining Process*. M.S. Thesis: University of Illinois at Urbana-Champaign, IL, US.
- [17] Zeng, W. M., Li, Z. C., Pei, Z. J., and Treadwell, C., (2004), Experimental investigation into rotary ultrasonic machining of alumina. Proceedings of the International Mechanical Engineering Congress and Exposition 2004, Anaheim, CA, US, November 13-19.

Chapter 10 - Titanium alloy - A Novel Measurement Method for Vibration Amplitude

Paper title:

Vibration amplitude in rotary ultrasonic machining: a novel measurement method and effects of process variables

Published in:

Journal of Manufacturing Science and Engineering (2011), Vol. 133, No. 3, pp. 034501-1– 034501-6

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Mohanlty, N.², Van Vleet, E.¹, and Treadwell, C.³

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

2. Department of Chemical Engineering, Kansas State University, Manhattan, KS 66506, USA

3. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Rotary ultrasonic machining (RUM) has been used to machine both brittle and ductile materials as well as composite materials. There are numerous reported studies about effects of various process variables on output responses. However, the current literature contains few articles about measurement methods of vibration amplitude in RUM and about effects of process variables on vibration amplitude. The lack of such knowledge has made it difficult to explain some experimentally observed phenomena in RUM and degraded the creditability of some experimental results with RUM. This paper, for the first time, presents a measurement method capable of measuring vibration amplitude during RUM machining. It also reports RUM experimental results on effects of cutting tool, ultrasonic power, workpiece material, tool rotation speed, and feedrate on ultrasonic amplitude. This study will fill some blanks in the literature and provide plausible explanations to some seemingly contradictory results reported in the literature.

Keywords: Grinding, Measurement, Rotary Ultrasonic Machining, Vibration Amplitude.

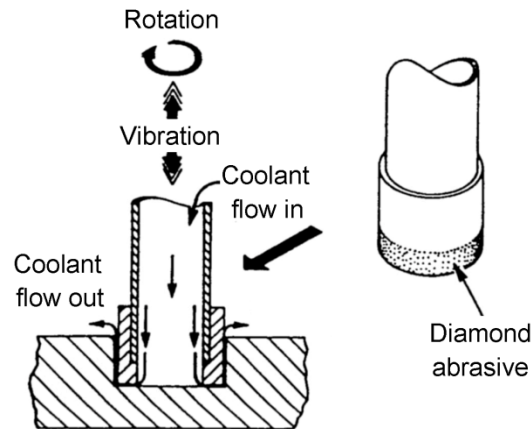
10.1 Introduction

Rotary ultrasonic machining (RUM) is a nontraditional machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining [1-3]. It has been used to machine various hard-to-machine materials including both brittle materials (such as advanced ceramics and glass) and ductile materials (such as titanium and stainless steel), as well as composite materials [4-12].

Figure 10.1 is the schematic illustration of RUM. The cutting tool is a core drill with metal-bonded diamond abrasives. During machining, the rotating tool vibrates axially at an ultrasonic frequency and moves along its axial direction towards the workpiece. Coolant pumped

through the core of the drill washes away the swarf and prevents the tool from jamming and overheating.

Figure 10.1 Illustration of rotary ultrasonic machining.



A through literature search has resulted in very few papers about measurement methods of vibration amplitude in RUM and about effects of RUM process variables on vibration amplitude. Prabhakar [1] built a measurement system for vibration amplitude in RUM using an optical vibration sensor consisting of an LED (light-emitting diode) and photoconductive transistor. The optical sensor was placed directly below the tool. Affixed to the bottom face of the tool was an aluminum foil serving as the reflector. The LED and the transistor were mounted side by side such that the light emitted by the LED could not directly shine on the transistor but the light emitted by the LED would be reflected to the transistor by the vibrating tool. This would induce a current in the transistor and the magnitude of the electrical signal was proportional to the vibration amplitude of the tool. Using this measurement system, he obtained the relationship between ultrasonic power and vibration amplitude without RUM machining. However, he did not report effects of other process variables on vibration amplitude. It is noted that this measurement system could not be used to measure vibration amplitude during RUM machining. Additional vibration amplitude measurement methods have been reported for

applications other than RUM [13-22]. They can potentially be used for vibration measurement in RUM. However, none of them can measure vibration amplitude during RUM machining.

A method used in industry to measure vibration amplitude in RUM involves a dial indicator. It has not been reported in the publically available literature. The details of this method will be provided in Section 10.2 of this paper (since this method will be used as a comparison to the novel measurement method reported in this paper). Once again, this method is not capable of measuring vibration amplitude during RUM machining. Furthermore, as shown later in Section 10.3.1, the measurement accuracy of this method is low.

Because no measurement methods have been available that can be used to measure vibration amplitude during RUM machining, there are no reported relationships between process variables and vibration amplitude during RUM machining. Therefore, it has been everyone's guess regarding the exact role of vibration amplitude in RUM. This, in turn, has degraded the creditability of some reported relationships between process variables (tool rotation speed; feedrate or constant pressure; ultrasonic vibration amplitude and frequency; diamond type, grit size, and concentration; or bond type for the cutting tool) and output responses (material removal rate, cutting force, surface roughness, edge chipping, and tool wear) in RUM. For example, if two tools with two different diamond grit sizes were tested and the results showed that one tool had lower tool wear rate, one could not be certain that the difference was caused by the difference in grit size unless both tools had the same vibration amplitude. Therefore, it is highly desirable to develop methods capable of measuring vibration amplitude during RUM machining and, using these methods, to experimentally determine the effects of process variables on vibration amplitude during RUM machining.

This paper reports a novel measurement method for vibration amplitude during RUM machining. In addition, it reports RUM experimental results on effects of cutting tool, ultrasonic power, workpiece material, tool rotation speed, and feedrate on vibration amplitude. It also compares the vibration amplitude during RUM machining measured using this novel method and that without RUM machining measured using the dial indicator method.

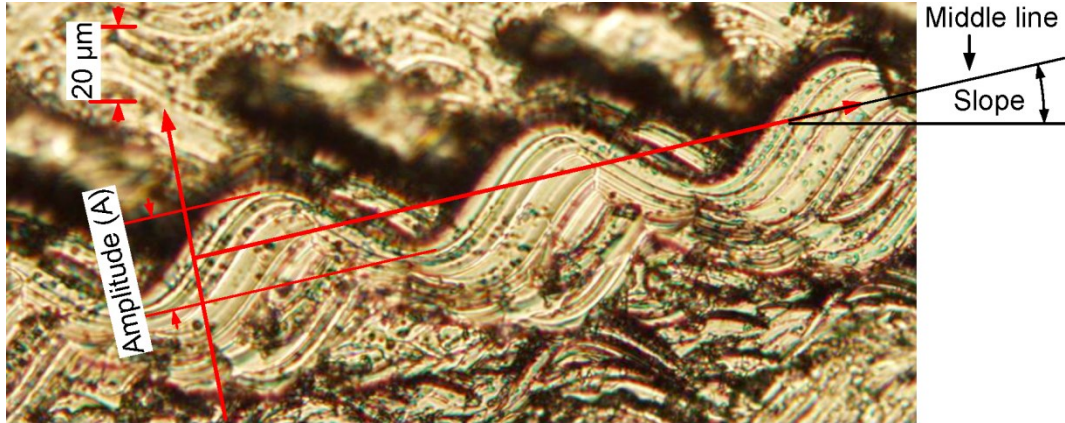
10.2 The novel measurement method, the dial indicator method, and other experimental conditions

10.2.1 The novel measurement method

The novel measurement method involves using a microscope to observe the machined surface by RUM. Since the cutting tool in RUM is a core drill, the process will produce a hole and a rod after the core drill cuts through the workpiece thickness. During machining, diamond grains fixed on the outer and inner surfaces of the tool leave machining marks on the surfaces of the machined hole and rod, respectively. These machining marks exhibit the trajectories of diamond grains relative to the machined surfaces. The peak-to-valley distance of each trajectory will correspond to the vibration amplitude (peak-to-peak amplitude) of the tool during RUM machining. To measure this vibration amplitude, high-magnification pictures were taken on the machined rod surfaces using a microscope. The method used here is similar, to a certain degree, to that in the quick stop experiments [23-25] for metal-cutting research where the cutting process is “frozen” for observations. The vibration amplitude exhibited on the rod surface is the actual vibration amplitude during RUM. However, the measurement (with a microscope) is taken after the machining is stopped.

Figure 10.2 shows an example of such microscope pictures and illustrates the measurement of vibration amplitude (A) as labeled.

Figure 10.2 Measurement of vibration amplitude on a microscopic picture.



The method used here is similar, to a certain degree, to that in the quick stop experiments [23-25] for metal-cutting research where the cutting process is “frozen” for observations. The vibration amplitude exhibited on the rod surface is the actual vibration amplitude during RUM. However, the measurement (with a microscope) is taken after the machining is stopped.

As illustrated later in this paper, these machining marks are observable only on metal workpieces. This explains why this method was not reported before since most prior research on RUM was done on brittle materials such as ceramics.

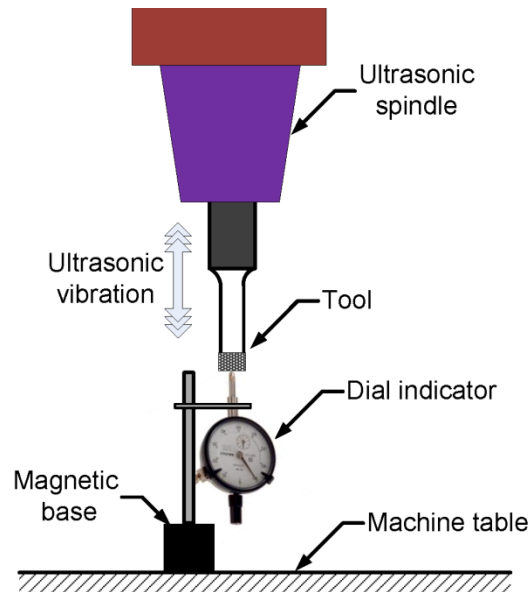
10.2.2 The dial indicator method

The dial indicator method was used in industry to measure vibration amplitude in RUM. As shown in Figure 10.3, the dial indicator was fixed onto the arm of the magnetic base, and the magnetic base was mounted on the machine table. The arm of the magnetic base was adjusted so that the pointer of the dial indicator touched the end surface of the tool. The reading on the dial indicator at this point in time was taken as the initial value (before ultrasonic vibration was turned on). After turning on the ultrasonic power, the pointer on the dial indicator would move and the reading then was taken as the final value. Because the frequency of ultrasonic vibration

is very high (typically 20 kHz), the pointer of the dial indicator was relatively steady, enabling the final value be read easily. As mentioned in the introduction section, this method cannot be used to measure the vibration amplitude during RUM machining.

In order to provide a comparison to the novel method, this method was also used to measure the vibration amplitude for some test conditions. For each test condition, several measurements were taken with the pointer of the dial indicator touching different locations on the tool end surface. The differences among these measurements under the same test condition were negligibly small. The average values of these measurements are presented in this paper.

Figure 10.3 Measurement of vibration amplitude with the dial indicator method.



10.2.3 Other experiment conditions

The machining experiments were performed on a Sonic-Mill Series 10 RUM machine (Sonic-Mill, Albuquerque, NM, USA). Five diamond tools (NBR Diamond tool Corp., LaGrangeville, NY, USA) were tested. The details of these tools are shown in Figure 10.4 and Table 10.1. These tools were different in as least one of the three specifications: weight, tuning

length (as indicated in Figure 10.4), and outer diameter. Quakercool 6010 (Murdock Industrial Supply Co., Wichita, KS, USA) water-soluble cutting fluid was used as coolant and diluted with water at a ratio of 1 to 14.

In the rest of this paper, unless indicated otherwise, the presented values of vibration amplitude are those during RUM machining, measured with the novel method. Two holes were drilled for each test condition of RUM experiments. Two pictures were taken at two different locations on each machined rod using a microscope (Model BX41M Olympus Inc. Tokyo, Japan). The eyepiece of the microscope had a magnification of 10 and the objective lens had a magnification of 10. The combination of the two gave a total magnification of 100.

Figure 10.4 Five different tools used in this study.



Table 10.1 Specifications of the tools.

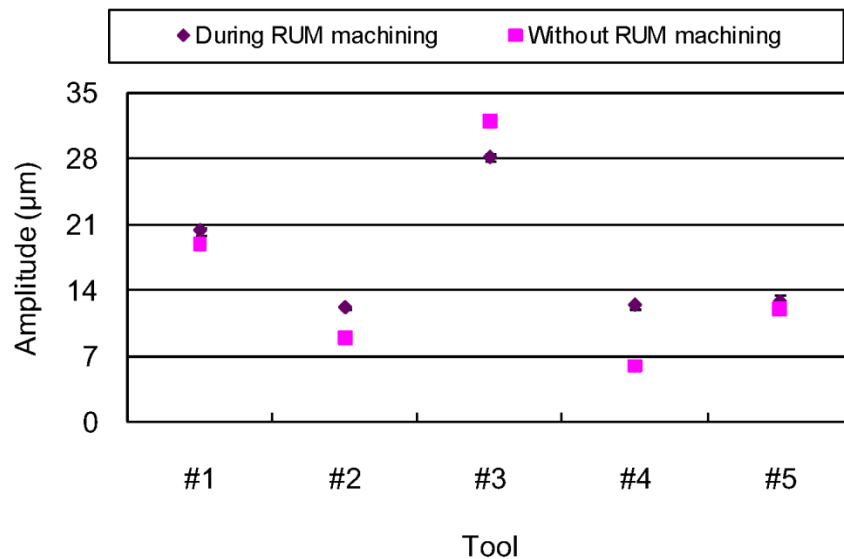
Tool identification	Diameter (mm)	Tuning length (mm)	Weight (g)
#1	9.5	44.2	25.2
#2	12.7	43.2	27.7
#3	12.7	60.2	33.2
#4	19.1	45.5	37.7
#5	22.2	42.9	42.5

10.3 Experimental results and discussion

10.3.1 Effects of cutting tool on vibration amplitude

Effects of cutting tool on vibration amplitude during RUM machining (measured with the novel method) are shown in Figure 10.5. Note that these tests were conducted with the same ultrasonic power setting (30%). It can be seen that Tools #2, #4, and #5 had about the same vibration amplitude, but Tools #1 and #3 had higher values of vibration amplitude.

Figure 10.5 Effects of cutting tool on vibration amplitude.



Workpiece material = Stainless steel

Ultrasonic power = 30%

Feedrate = 0.015 mm/s

Tool #1: Tool rotation speed = 3000 rpm, Feedrate = 0.0003 mm/rev

Tool #2: Tool rotation speed = 2251 rpm, Feedrate = 0.0004 mm/rev

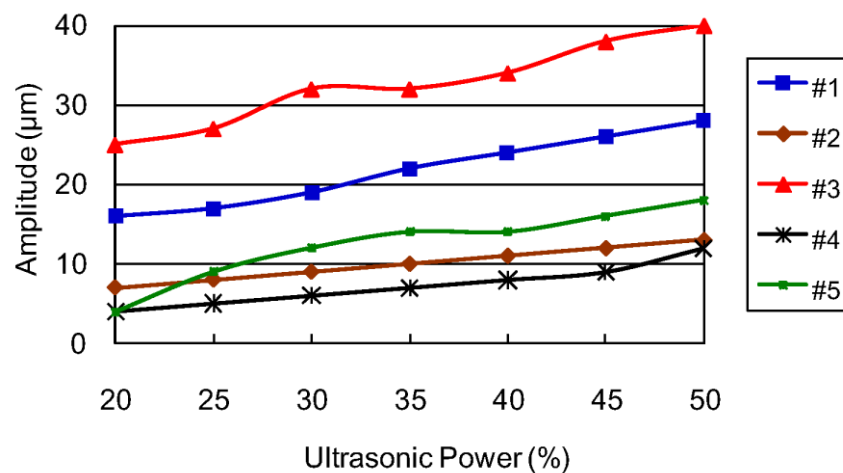
Tool #3: Tool rotation speed = 2251 rpm, Feedrate = 0.0004 mm/rev

Tool #4: Tool rotation speed = 1497 rpm, Feedrate = 0.0006 mm/rev

Tool #5: Tool rotation speed = 1286 rpm, Feedrate = 0.0007 mm/rev

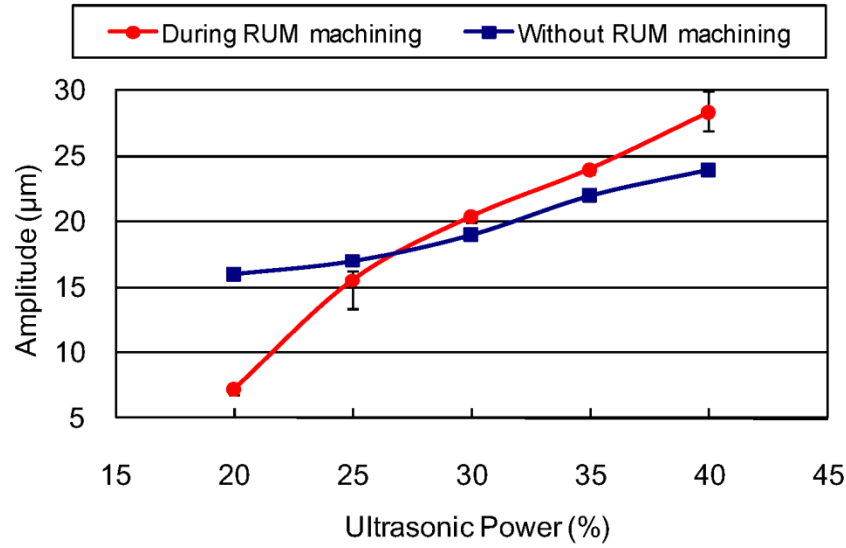
Figure 10.6 also shows effects of cutting tool on vibration amplitude without RUM machining (measured with the dial indicator method). The results show a similar finding. For different tools, vibration amplitude varied when ultrasonic power was kept at the same level (30%). Furthermore, almost at every setting of ultrasonic power, different tools had different values of vibration amplitude.

Figure 10.6 Effects of ultrasonic power on vibration amplitude (measure with the dial indicator method) for five tools (#1, #2, #3, #4, and #5).



As shown in Figure 10.5 (as well as in Figure 10.7), vibration amplitude without RUM (measured with the dial indicator method) had similar trends as during RUM machining (measured with the novel method). However, comparing with the novel method, the dial indicator method tended to produce higher amplitude values when ultrasonic power was lower, but lower amplitude values when ultrasonic power was higher.

Figure 10.7 Effects of ultrasonic power on vibration amplitude.



Tool #1
 Workpiece material = Stainless steel
 Feedrate = 0.015 mm/s (0.0003 mm/rev)
 Tool rotation speed = 3000 rpm

The finding (that vibration amplitude differs for different tools at the same setting of ultrasonic power) is the first in the literature. (Although it was not explicitly stated in any published papers that vibration amplitude would remain the same for different tools, it was clear that such assumption was used when some experimental results were discussed or explained.) This finding can provide explanations to some seemingly contradictory experimental results reported in the literature. When different tools were used to test effects of other process variables on output responses (material removal rate, cutting force, surface roughness, edge chipping, or tool wear), the effects of the process variable could be shadowed by the effects of vibration amplitude if these tools had different vibration amplitude values. For example, the RUM cutting force model by Qin et al. [12] predicted that the cutting force would increase as the number of diamond grains increased. However, experiments reported by Churi et al. [7] show that the

cutting force decreased as the numbers of diamond grains (diamond concentration) increased. The finding reported here in this paper can provide a plausible explanation for such inconsistency. The influences of diamond grain number on cutting force were predicted based on the assumption that everything else was the same when the diamond grain number changed [12]. In experiments, two different tools were used, one with diamond concentration of 80, and the other 100 [7]. There was no guarantee that these two tools were made exactly the same except diamond concentration. It might be that the tool with larger diamond concentration (hence larger diamond grain number) had higher vibration amplitude than the other tool. Both model predictions [12] and experimental results [6] show that the cutting force decreased as the vibration amplitude increased.

10.3.2 Effects of ultrasonic power on vibration amplitude

Figure 10.7 shows effects of ultrasonic power on vibration amplitude. It can be seen that, when ultrasonic power increased from 20% to 40%, vibration amplitude during RUM machining increased from 7 μm to 28 μm , while the vibration amplitude without RUM machining increased from 15 μm to 24 μm .

The effects of ultrasonic power on vibration amplitude without machining (measured with the dial indicator method) are also presented in Figure 10.6. For all the five different tools, vibration amplitude without RUM machining increased with the increase in ultrasonic power.

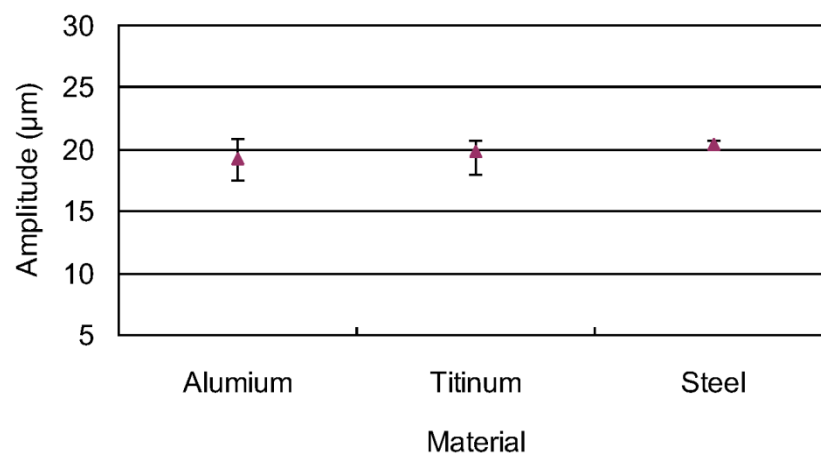
It has been commonly stated in the literature that ultrasonic power determines vibration amplitude [1, 6-11]. There are some reports [1] on experimentally determined relationships between ultrasonic power and vibration amplitude. It is noted that the values of vibration amplitude reported in the literature before were those without RUM machining. This paper is the

first to present experimentally determined relationships between ultrasonic power and vibration amplitude during RUM machining.

10.3.3 Effects of workpiece material on vibration amplitude

Six different workpiece materials were used to determine their effects on vibration amplitude. These workpiece materials were stainless steel, titanium, aluminum, advanced ceramic (Al_2O_3), ceramic matrix composite (CMC), and graphite. The novel method to measure the vibration amplitude was applicable only to the first three workpiece materials. The trajectories left by the diamond grains on the machined rod surfaces were visible for the first three materials (aluminum, titanium, and stainless steel), but not visible for the other three materials. This provides an explanation about why this novel method was not reported before because prior research on RUM was done almost exclusively on brittle materials such as ceramics.

Figure 10.8 Effects of workpiece material on vibration amplitude.



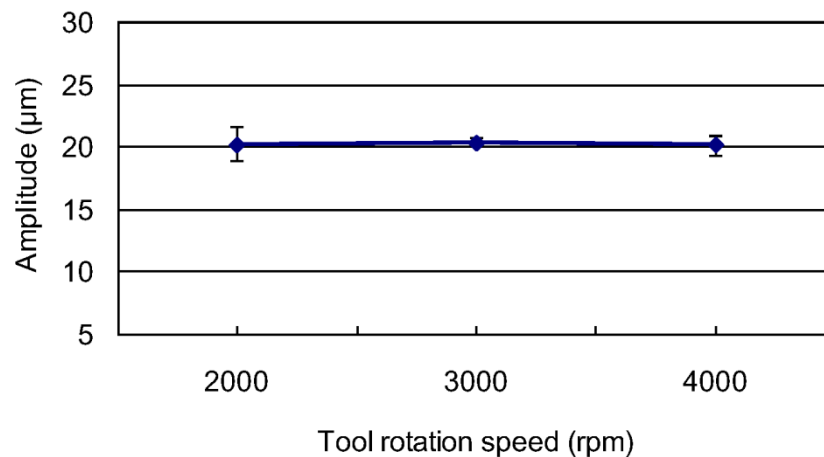
Tool #1
 Ultrasonic power = 30 %
 Feedrate = 0.015 mm/s (0.0003 mm/rev)
 Tool rotation speed = 3000 rpm

Figure 10.8 shows the effects of workpiece material on vibration amplitude. It can be seen that vibration amplitude changed little for different workpiece materials. This is good news for RUM research. This means that, if the same tool is used to study effects of workpiece material on output responses (material removal rate, cutting force, surface roughness, edge chipping, or tool wear), there will be no confounding effects between workpiece material and vibration amplitude.

10.3.4 Effects of tool rotation speed on vibration amplitude

Effects of tool rotation speed on vibration amplitude are shown in Figure 10.9. Tool rotation speed did not have significant effects on vibration amplitude in the range of 2000 to 4000 rpm. Tool rotation speed had significant effects on the wavelength of the sine-wave shaped trajectories on the machined rod surfaces. The wavelength increased as tool rotation speed increased.

Figure 10.9 Effects of tool rotation speed on vibration amplitude.

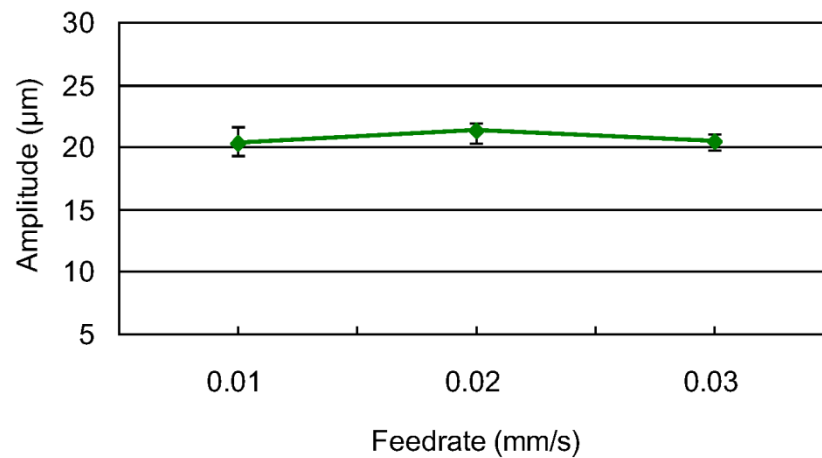


Tool #1
 Workpiece material = Stainless steel
 Ultrasonic power = 30 %
 Feedrate = 0.015 mm/s (0.0003 mm/rev)

10.3.5 Effects of feedrate on vibration amplitude

Effects of feedrate on vibration amplitude are shown in Figure 10.10. There seemed to be little fluctuations in vibration amplitude when feedrate changed from 0.01 to 0.03 mm/s (0.0002 to 0.0006 mm/rev). Therefore, it can be concluded that feedrate had negligible effects on vibration amplitude. However, the feedrate did have noticeable effects on the slope of the middle line that the sine-wave shaped trajectories were based on. A higher feedrate would generate a larger slope.

Figure 10.10 Effects of feedrate on vibration amplitude.



Tool #1
Workpiece material = Stainless steel
Ultrasonic power = 30 %
Tool rotation speed = 3000 rpm

10.4 Conclusions

This paper presented a novel method to measure the vibration amplitude in RUM during machining, the only method reported in the literature that possesses such capability. It also compared this novel method with the dial indicator method that can only measure the vibration

amplitude without RUM machining. It reported experimental results about the effects of input variables on vibration amplitude. Major conclusions are as follows.

- (1) The vibration amplitude without RUM machining (measured with the dial indicator method) has similar trends with the vibration amplitude during RUM machining (measured with the novel method).
- (2) The vibration amplitude during RUM machining, as well as that without RUM machining, was different when using tools that were different in weight, length, or diameter.
- (3) Excluding cutting tool, ultrasonic power was the only input variable significantly affecting vibration amplitude. Vibration amplitude showed no significant variations with changes in workpiece material, tool rotation speed, and feedrate.

The above results are the first reported in the literature. They provide explanations to some contradictory reports in the literature about the effects of input variables on some output responses (including material removal rate, cutting force, surface roughness, edge chipping, and tool wear). They also give readers a certain level of confidence in the RUM experimental results previously reported because vibration amplitude would stay the same for different test conditions (excluding ultrasonic power and cutting tool).

Acknowledgments

The work was supported by the National Science Foundation through Award CMMI-0900462. The authors would like to thank Mr. Bruno Renzi at NBR Diamond Tool Corporation for providing the diamond tools, and Mr. Timothy Deines at Kansas State University for providing technical assistance in making fixture and setting up the RUM machine.

References

- [1] Prabhakar, D., 1992, "Machining Advanced Ceramic Materials Using Rotary Ultrasonic Machining Process," M.S. Thesis, University of Illinois at Urbana-Champaign, IL, US.
- [2] Schwartz, M., 1992, *Handbook of Structural Ceramics*, McGraw-Hill, Inc., New York, US.
- [3] Dam, H., Jensen, J., and Quist, P., 1993, "Surface Characterization of Ultrasonic Machined Ceramics with Diamond Impregnated Sonotrode," *Proceedings of the International Conference on Machining of Advanced Materials*, Gaithersburg, MD, US, July 20-22, pp. 125-133.
- [4] Tyrrell, W.R., 1970, "New Method for Machining Hard and Brittle Materials," *SAMPE Quart.*, **1**(2), pp. 55-59.
- [5] Pei, Z.J., Khanna, N., and Ferreira, P.M., 1995, "Rotary Ultrasonic Machining of Structural Ceramics: a Review," *Ceram, Eng. Sci. Proc.*, **16**(1), pp. 259-278.
- [6] Churi, N.J., Li, Z.C., Pei, Z.J., and Treadwell, C., 2006 "Rotary Ultrasonic Machining of Titanium Alloy: Effects of Machining Variables," *Mach. Sci. Technol.*, **10**(3), pp. 301-321.
- [7] Churi, N.J., Li, Z.C., Pei, Z.J., and Treadwell, C., 2007, "Rotary Ultrasonic Machining of Titanium Alloy (Ti-6Al-4V): Effects of Tool Variables," *Int. J. of Precision Technology*, **1**(1), pp. 85-96.
- [8] Churi, N.J., Li, Z.C., Pei, Z.J., and Treadwell, C., 2005, "Rotary Ultrasonic Machining of Titanium Alloy: a Feasibility Study," *Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition*, Orlando, FL, US, November 5-11, pp. 885-892.

- [9] Cong W.L., Pei, Z.J., Churi, N., and Wang, Q.G., 2009, "Rotary Ultrasonic Machining of Stainless Steel: Design of Experiments," *Trans. North Am. Manuf. Res. Inst. SME*, **37**, pp. 261-268.
- [10] Cong W.L., Pei, Z.J., Van Vleet, E., and Wang, Q.G., 2009, "Surface Roughness in Rotary Ultrasonic Machining of Stainless Steels," *Proceedings of the 2009 Industrial Engineering Research Conference*, Miami, FL, US, May 30 - June 3.
- [11] Li, Z.C., Jiao, Y., and Deines, T.W., 2005, "Rotary Ultrasonic Machining of Ceramic Matrix Composites: Feasibility Study and Designed Experiments," *Int. J. Mach. Tools Manuf.*, **45**(12-13), pp. 1402-1411.
- [12] Qin, N., Pei, Z.J., Treadwell, C., and Guo, D.M., 2009, "Physics-Based Predictive Cutting Force Model in Ultrasonic-Vibration-Assisted Grinding for Titanium Drilling," *J. Manuf. Sci. Eng.*, **131**(4), pp. 1-9.
- [13] Hueners, B.W., 1983, "Absolute Ultrasonic Amplitude Measurement, Calibration and Troubleshooting of A Wire Bonder Using A Laser Interferometer," *Int. J. Hybrid Microelectron*, **6**(1), pp. 167-170.
- [14] Bindal, V.N., Jain, S.K., and Kumar, Y.A., 1986, "A Laser Interferometer for Vibration Amplitude Measurement of Power Ultrasonic Sources," *Indian J. Pure Appl. Phys.* **24**(12), pp. 584-587.
- [15] Boucaud, A., Felix, N., Pizarro, L., and Patat, F., 1999, "High Power Low Frequency Ultrasonic Transducer: Vibration Amplitude Measurements by An Optical Interferometric Method," *Proceedings of IEEE Ultrasonics Symposium*, Caesars Tahoe, NV, US, October 17-20, pp. 1095-1098.

- [16] Yoneda, K., Tawata, M., and Hattori, S., 1979, "Measurement of very small vibration amplitude in ultrasonic transducer by means of a laser probe," *Proceedings of IEEE Ultrasonics Symposium*, New Orleans, LA, USA, September 26-28, pp. 51-55.
- [17] Leonov, G.V., Khmelev, V.N., Savin, I.I., Abramenko, D.S., 2005, "Automation of the Amplitude Measurement Process of Ultrasonic Oscillatory Systems Irradiating Surface," *Proceedings of the 6th Annual International Siberian Workshop and Tutorials on Electron Devices and Materials*, Erlagol, Altai, Russia, July 1-5, pp. 64-67.
- [18] Khmelev, V.N., Abramenko, D.S., Barsukov, R.V., and Lebedev, A.N., 2008, "Usage Features of Contact and Noncontact Measuring Methods of Oscillation Amplitude During Adjustment Process of Ultrasonic Devices," *Proceedings of the 9th International Workshop and Tutorials on Electron Devices and Materials*, Novosibirsk, Novosibirsk, Russia, July 1-5, pp. 223-226.
- [19] Yarnitsky, Y., and Braun, S., 1967, "Vibration-Amplitude Measurement on Ultrasonic Drill," *Microtecnic*, **21**(3), pp. 297-298.
- [20] Yost, W.T., and Cantrell, J.H., 1992, "Absolute Ultrasonic Displacement Amplitude Measurements with A Submersible Electrostatic Acoustic Transducer," *Rev. Sci. Instrum.*, **63**(9), pp. 4182-4188.
- [21] Golyamina, I.P., Polyakov, Z.I., and Khlopotunova, N.A., 1982, "Meter for Monitoring the Vibration Amplitude of An Ultrasonic Tool," *Instrum. Exp. Tech.*, **25**(5), pp. 1304-1308.
- [22] Lazara, K., Zayas, J.M., and Zajac, A., 1975, "X-Ray Measurement of An Ultrasonic Wave Amplitude in A Crystal," *J. Acoust. Soc. Am.*, **58**(2), pp. 471-474.

- [23] Philip, P.K., 1971, "Study of the performance characteristics of an explosive quick- stop device for freezing cutting action," Int. J. Mach. Tool Design and Research, **11**(2), pp. 133-144.
- [24] Vorm, T., 1976, "Development of a quick-stop device and an analysis of the frozen-chip technique," Int. J. Mach. Tool Design and Research, **16**(4), pp. 241-250.
- [25] Griffiths, B.J., 1986, "Development of a quick-stop device for use in metal cutting hole manufacturing processes," Int. J. Mach. Tool Design and Research, **26**(2), pp. 191-203.

Chapter 11 - Titanium alloy - A Study on Cutting Temperature

Paper title:

Experimental study on cutting temperature in rotary ultrasonic machining

Published in:

Proceedings of North American Manufacturing Research Institution of SME (2011), Vol. 39, pp. 369-376.

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Feng, Q.¹, Deines, T.W.¹, and Treadwell, C.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
2. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Rotary ultrasonic machining (RUM) has been used to machine various difficult-to-machine materials. Investigations have been reported regarding effects of input variables on several output variables (including cutting force, torque, surface roughness, edge chipping, material removal rate, and tool wear) in RUM. However, there is no report on any study on cutting temperature in RUM. This paper presents an experimental study on cutting temperature in RUM using titanium as workpiece material. Results show that cutting temperature with ultrasonic vibration was lower than that without ultrasonic vibration. Higher feedrate and lower coolant flow rate caused higher cutting temperature.

Keywords: Diamond, Drilling, Grinding, Rotary ultrasonic machining, Temperature, Titanium alloy.

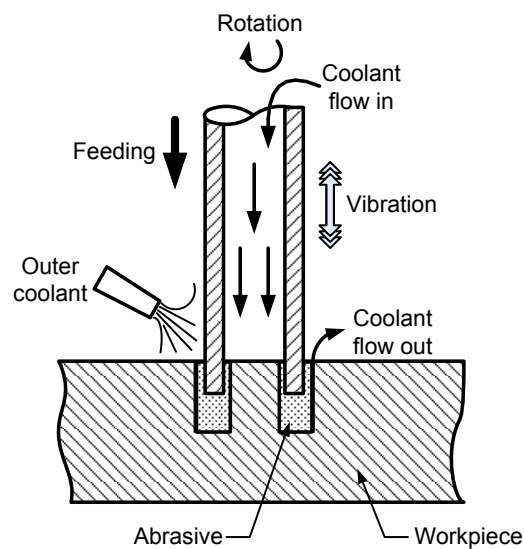
11.1 Introduction

Rotary ultrasonic machining (RUM), as illustrated in Figure 11.1, is a hybrid machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrates axially at an ultrasonic frequency and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf and prevents the tool from jamming and overheating.

RUM has been used to machine various materials including alumina [Li et al. 2005ab, 2006, 2010, Jiao et al. 2005ab], composites [Li et al. 2005c], silicon carbide [Churi et al. 2007c], stainless steel [Cong et al. 2009ab, 2010], and titanium [Churi et al. 2005, 2006, 2007ab]. Effects of input variables (such as ultrasonic power, tool rotation speed, feedrate, coolant condition, diamond grains size, diamond concentration, and metal bond type) on output variables (including

cutting force, torque, surface roughness, edge chipping, material removal rate, and tool wear) in RUM have been studied [Churi et al. 2005, 2006, 2007abc, Cong et al. 2009ab, 2010, Jiao et al. 2005ab, Li et al. 2004, 2005abc, 2006, 2010, Pei et al. 1995, Wang et al. 2009, Wang et al. 2009, Zeng et al. 2005]. However, the literature does not contain any report about cutting temperature in RUM.

Figure 11.1 Illustration of rotary ultrasonic machining.



In RUM (and other machining processes), high cutting temperatures strongly influence tool life and quality of machined parts [O’Sullivan and Cotterell 2002]. Cutting temperature is among the factors determining whether coolant needs to be used [O’Sullivan and Cotterell 2002, Li and Shih 2007]. Therefore, it is important to study the cutting temperature in RUM.

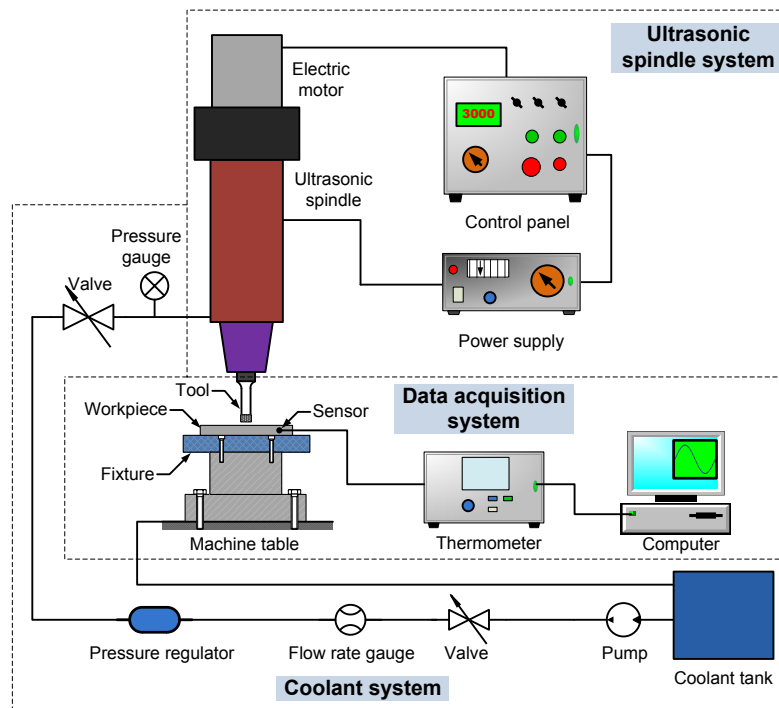
This paper reports an experimental investigation on cutting temperature in RUM of titanium. There are four sections in this paper. Following this introduction section, Section 11.2 describes experimental conditions and measurement procedures. Section 11.3 presents and discusses experimental results. Finally, conclusions are drawn in Section 11.4.

11.2 Experimental conditions and measurement procedures

11.2.1 Experimental set-up

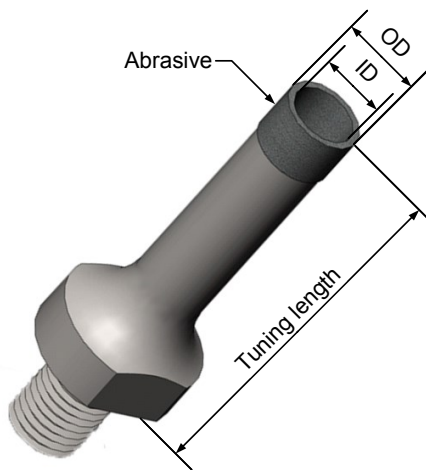
Machining experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 11.2. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system was comprised of an ultrasonic spindle, a power supply, and a motor. The power supply converted 60 Hz electrical supply to high-frequency (20 kHz) AC output. This high frequency electrical energy was provided to a piezoelectric converter (located in the ultrasonic spindle) that converted electrical energy into mechanical vibration. The amplitude of ultrasonic vibration was adjusted by changing the setting on the power supply. The motor attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds were obtained by adjusting the motor speed controller on the control panel.

Figure 11.2 Experimental set-up.



The tool, as illustrated in Figure 11.3, was a metal-bonded diamond core drill (NBR Diamond tool corp., LaGrangeville, NY, USA). The outer and inner diameters (OD and ID) of the tool were 9.54 and 7.82 mm, respectively, and the tuning length was 44.5 mm. The metal bond was of B type. The size of diamond grains was mesh 60/80 and the diamond concentration was 100.

Figure 11.3 Illustration of the tool.



The workpiece material was titanium alloy (Ti-6Al-4V). Its tensile strength was 950 MPa, thermal conductivity $21 \text{ W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$, and Vickers hardness 300. The size of the workpieces was $15\times 15\times 6.4 \text{ mm}$.

11.2.2 Experimental conditions

Based on past experiences with RUM of titanium and due to limitations of the experimental set-up (for example, vibration frequency was fixed at 20 kHz on the machine), the following input variables were changed in the experiments:

- Tool rotation speed: Rotational speed of tool;

- Feedrate: Feedrate of tool;
- Ultrasonic power: Percentage of power from ultrasonic power supply, which controls the ultrasonic vibration amplitude;
- Outer coolant: Additional coolant pumped to the outside of the tool and aimed at the gap between the tool outer surface and the machined hole in the workpiece, as illustrated in Figure 11.1;
- Coolant pressure: Pressure of coolant;
- Coolant flow rate: Flow rate of coolant.

Values of these input variables are listed in Table 11.1. Four holes were drilled under each condition.

Table 11.1 Values of input variables.

Variable	Value
Tool rotation speed (rpm)	1500; 3000; 4500; 6000
Feedrate (mm/s)	0.02; 0.04; 0.06
Ultrasonic power (%)	0; 20; 40; 60
Coolant pressure (psi)	20; 30; 40
Coolant flow rate (lpm)	0.5; 1.5; 3.0

11.2.3 Experimental procedures

Methods reported to experimentally measure cutting temperature include thermocouples (such as tool-work thermocouples and commercial thermocouples) [Li and Shih 2007, DeVries et al. 1976], thermal paint method [Koch and Levi 1971], powder and films method [Kato et. al. 1976, Walton et. al. 2006], pyrometer method [Lin et. al. 1992, Ueda et. al. 1998], infrared camera method [Muller-Hummel and Lahres 1994, Dorr et. al. 2003], and fiber optical method [Ueda et. al. 2007]. After comparing advantages and disadvantages of these methods,

commercial thermocouples embedded in the workpiece were selected to measure cutting temperatures in this study.

For RUM, it is difficult to directly measure the cutting temperature at the interface between the workpiece material and the tool working surface (i.e. the end surface of the tool). For example, it is difficult to fix any thermocouple very close to the interface since the tool rotates at a high speed.

The temperature measurement used in this study is illustrated in Figure 11.4. A blind hole perpendicular to the tool feeding direction and along the radius direction of the hole was drilled into the workpiece. The distance between the end of this blind hole and the cylindrical surface of the machined hole was 0.5 mm. A K-type thermocouple (Model SC-GG-K-30-36, OMEGA Engineering, Inc. Stamford, CT, USA) was positioned inside the blind hole. To fix the thermocouple in place, the gap between the thermocouple and the blind hole was filled with a thermal paste (Arctic Silver 5, Arctic Silver Incorporated, Visalia, CA, USA). The electrical signals from the thermocouple were collected using a digital thermometer (Model HH147U, OMEGA Engineering, Inc. Stamford, CT, USA). Then the measured data were recorded and displayed on a computer with the help of Temp-monitor software (Version S2, OMEGA Engineering, Inc. Stamford, CT, USA). A typical temperature-versus-time curve is shown in Figure 11.5. The sampling rate was set at 1 per second. The temperature values reported in this paper are the maximum temperature readings during each drilling test.

Figure 11.4 Illustration of temperature measurement in RUM.

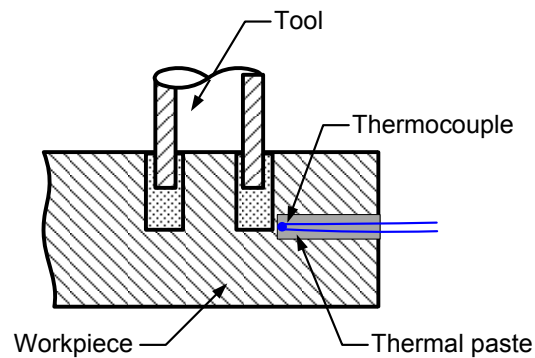
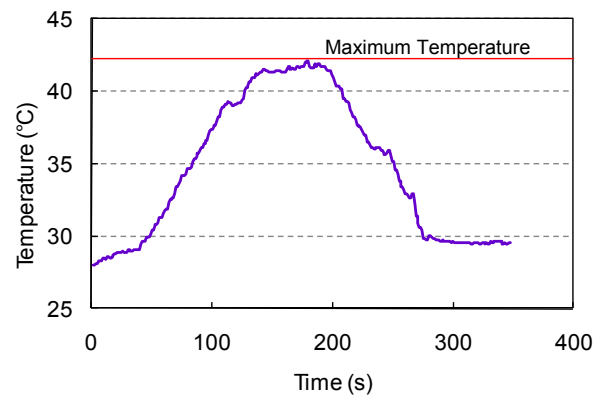


Figure 11.5 A typical curve of temperature versus machining time.



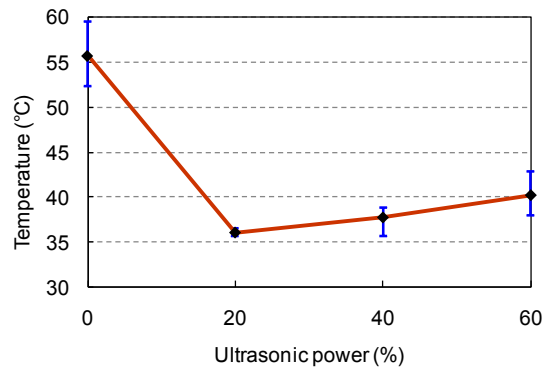
It is important to note that the temperature measured in this study is not the cutting temperature at the interface between the workpiece material and the tool working surface. The measured temperature should be lower than the temperature at the interface. However, the measured temperature has a certain relationship with the interface temperature. The authors are developing simulation models to estimate the interface temperature from the temperature data measured using this method.

11.3 Experimental results

11.3.1 Effects of ultrasonic power

Effects of ultrasonic power on cutting temperature are shown in Figure 11.6. Cutting temperatures when ultrasonic vibration were on (ultrasonic power = 20%, 40%, and 60%) were lower than that when ultrasonic vibration was off (ultrasonic power = 0). This is possibly due to the difference in contact mode between the tool end face and the workpiece. When there was no ultrasonic vibration, the contact between the tool end face and the workpiece was continuous. In contrast, when there was ultrasonic vibration, the contact was intermittent. This difference might lead to a difference in the amount of friction-generated heat. When ultrasonic power increased from 20% to 60%, there was an obvious (but not dramatic) increase in cutting temperature. The end points of the error bar for each data point are the minimum and maximum temperature values of the four measurements under each condition. The range of temperatures increased as ultrasonic power increased from 20% to 60%.

Figure 11.6 Effects of ultrasonic power on cutting temperature.



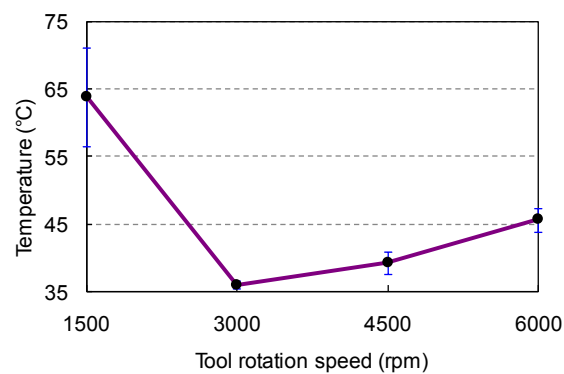
Tool rotation speed = 3000 rpm; Feedrate = 0.04 mm/s;
Coolant flow rate = 1.5 lpm; Coolant pressure = 30 psi;
With outer coolant.

Ultrasonic power determines the vibration amplitude. As ultrasonic power increases, the vibration amplitude will increase. This will increase the penetration depth of diamond grains into the workpiece material, increasing the interaction force between the diamond grain and the workpiece material. This could result in an increase of cutting temperature.

11.3.2 Effects of tool rotation speed

Effects of tool rotation speed on cutting temperature are shown in Figure 11.7. Cutting temperatures were measured when the tool rotation speeds were 1500 rpm, 3000 rpm, 4500 rpm, and 6000 rpm, respectively. The cutting temperature decreased sharply from 1500 rpm to 3000 rpm. But it gradually increased as the tool rotation speed increased from 3000 rpm to 6000 rpm. The lowest temperature was measured when tool rotation speed was 3000 rpm. When tool rotation speed was 1500 rpm, cutting temperature was the highest. When feedrate (in the unit of mm/s) was kept the same, a lower tool rotation speed would cause a higher depth of cut for individual diamond grains on the tool end face, leading to higher cutting force [Churi et al. 2006]. This might be the reason for the higher temperature when tool rotation speed was lower.

Figure 11.7 Effects of tool rotation speed on cutting temperature.



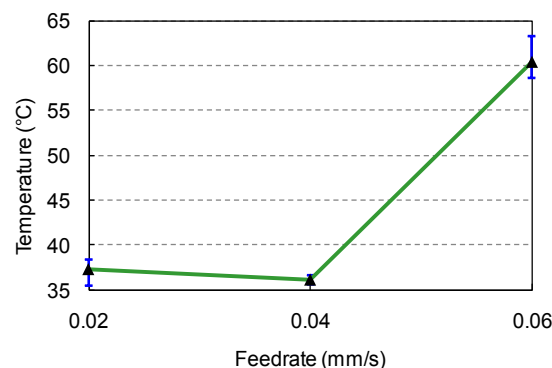
Ultrasonic power = 30%; Feedrate = 0.04 mm/s;
Coolant flow rate = 1.5 lpm; Coolant pressure = 30 psi;
With outer coolant.

Compared with the temperature difference between tool rotation speeds of 1500 rpm and 3000 rpm, the temperature difference between tool rotation speeds of 3000 rpm and 4500 rpm or between tool rotation speeds of 4500 rpm and 6000 rpm was much smaller. The range of the temperature when tool rotation speed was 1500 rpm was larger than those when tool rotation speed was 3000 rpm, 4500 rpm, or 6000 rpm.

11.3.3 Effects of feedrate

Effects of feedrate on cutting temperature are shown in Figure 11.8. When feedrate changed from 0.02 mm/s to 0.04 mm/s, there was nearly no change in cutting temperature, and the ranges of temperature when the feedrate was 0.02 mm/s and 0.04 mm/s were small. However, when the feedrate increased from 0.04 mm/s to 0.06 mm/s, cutting temperature increased dramatically and the temperature range became larger.

Figure 11.8 Effects of feedrate on cutting temperature.



Ultrasonic power = 30%; Tool rotation speed = 3000 rpm;
Coolant flow rate = 1.5 lpm; Coolant pressure = 30 psi;
With outer coolant.

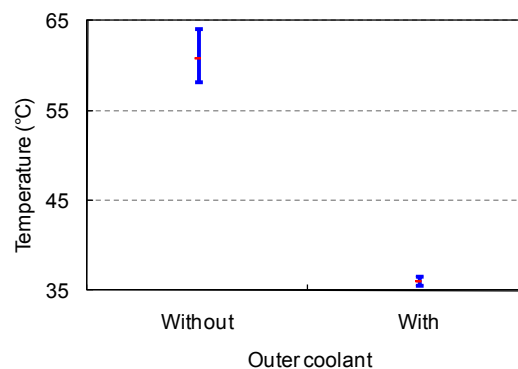
As the feedrate increased, the penetration depth of individual diamond grains into workpiece material would increase. This could increase the interaction force between the

diamond grain and workpiece material. Therefore, as feedrate increased (when other input variables were kept the same), much more heat could be generated. Furthermore, when this penetration depth became too large, the contact between the diamond grains and workpiece material might become continuous. This would further increase cutting temperature.

11.3.4 Effects of outer coolant

To evaluate how the outer coolant could affect cutting temperature, two groups of experiments were conducted (one with outer coolant and the other without). Figure 11.9 is a comparison of cutting temperatures in these two groups of experiments. It can be seen that cutting temperatures with additional outer coolant were much lower than those without outer coolant.

Figure 11.9 Effects of outer coolant on cutting temperature.



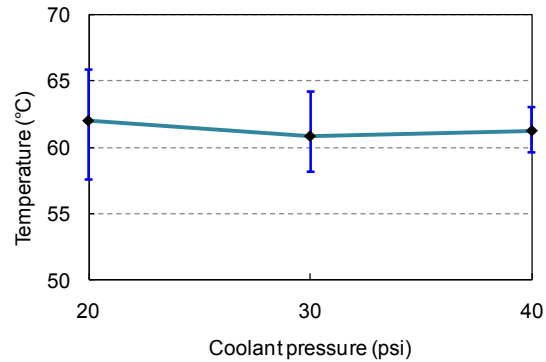
Ultrasonic power = 30%; Tool rotation speed = 3000 rpm; Feedrate = 0.04 mm/s;
Coolant flow rate = 1.5 lpm; Coolant pressure = 30 psi.

This result is intuitive. However, past experiments with RUM of titanium showed that the outer coolant affected some output variables, but not others. Understanding how the outer coolant affects cutting temperature can provide insights for mechanisms of its effects on various output variables.

11.3.5 Effects of coolant pressure

Experiments to evaluate effects of coolant pressure were conducted without outer coolant. Three levels of coolant pressure (20, 30, and 40 psi) were used. Coolant flow rate was kept at 1.5 lpm. The results are shown in Figure 11.10. It can be seen that coolant pressure has no obvious effects on cutting temperature. However, the range of cutting temperature became smaller as coolant pressure increased.

Figure 11.10 Effects of coolant pressure on cutting temperature.

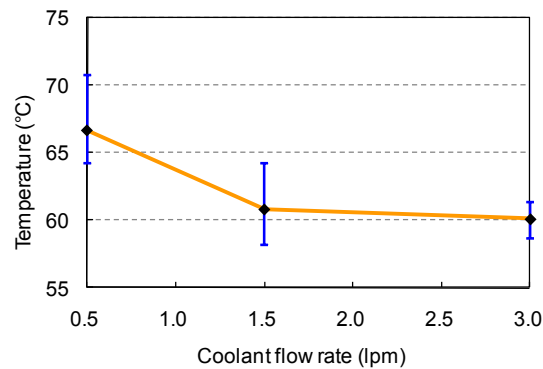


Ultrasonic power = 30%; Tool rotation speed = 3000 rpm; Feedrate = 0.04 mm/s;
Coolant flow rate = 1.5 lpm; Without outer coolant.

11.3.6 Effects of coolant flow rate

Experiments to evaluate effects of coolant flow rate were conducted without outer coolant. Three levels of coolant flow rate (0.5, 1.5, and 3.0 lpm) were used. Coolant pressure was kept at 30 psi. The results are depicted in Figure 11.11. It can be seen that the highest cutting temperature was measured when coolant flow rate was 0.5 lpm. There were no significant changes in cutting temperature when coolant flow rate changed from 1.5 lpm to 3 lpm. Higher coolant flow rate could help more coolant to reach the cutting interface and hence reduce cutting temperature.

Figure 11.11 Effects of coolant flow rate on cutting temperature.



Ultrasonic power = 30%; Tool rotation speed = 3000 rpm; Feedrate = 0.04 mm/s;
Coolant pressure = 30 psi; Without outer coolant.

11.4 Conclusions

This paper, for the first time, reported an experimental study on cutting temperature in RUM. It presented effects of three machining variables (ultrasonic power, tool rotation speed, and feedrate) and three coolant variables (outer coolant, coolant pressure, and coolant flow rate) on cutting temperature. The following conclusions can be drawn:

- (a) Cutting temperature with ultrasonic vibration was lower than that without ultrasonic vibration. When ultrasonic vibration was on, cutting temperature increased as ultrasonic power increased.
- (b) Lower feedrate led to higher cutting temperature.
- (c) As tool rotation speed increased, cutting temperature decreased to a value and then increased.
- (d) Outer coolant had significant effects on cutting temperature. Cutting temperatures with outer coolant were much lower than those without outer coolant.
- (e) Coolant pressure had no obvious effects on cutting temperature. As coolant flow rate increased, the cutting temperature decreased.

Due to limitations of the measurement method (thermocouple), the temperatures measured in this paper were not the cutting temperatures at the tool-workpiece interface. The measured temperatures should be significantly lower than those at the interface. Nevertheless, the experimental results were still valuable. They revealed effects of machining and coolant variables on cutting temperature in RUM for the first time in the literature. It is reasonable to assume that these input variables will have similar effects on the temperature at the tool-workpiece interface. Furthermore, the experimentally determined relations between input variables and cutting temperature can provide foundations for attempts to develop simulation models to predict cutting temperatures at the tool-workpiece interface.

Acknowledgements

The work was supported by the National Science Foundation through Grant No. CMMI-0900462. The authors would like to thank Professor Kamlakar Rajurkar at University of Nebraska at Lincoln for his advice and suggestions to improve the manuscript. The authors gratefully extend their acknowledgements to Mr. Bruno Renzi at N.B.R. Diamond tool Corp. for supplying the diamond core drill.

References

Churi NJ, Li ZC, Pei ZJ, Treadwell C (2005) Rotary ultrasonic machining of titanium alloy: a feasibility study. *Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition (IMECE 2005)*, 885-892, Orlando, FL, USA, November 5-11.

Churi NJ, Pei ZJ, Treadwell C (2006) Rotary ultrasonic machining of titanium alloy: effects of machining variables. *Machining Science and Technology* 10 (3), 301-321.

Churi NJ, Pei ZJ, Treadwell C (2007a) Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables. *International Journal of Precision Technology* 1 (1), 85-96.

Churi NJ, Pei ZJ, Treadwell C (2007b) Wheel wear mechanisms in rotary ultrasonic machining of titanium. *Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition (IMECE 2007)*, 399-407, Seattle, WA, USA, November 11-15.

Churi NJ, Pei ZJ, Treadwell C, Shorter D (2007c) Rotary ultrasonic machining of silicon carbide: designed experiments. *International Journal of Manufacturing Technology and Management* 12 (1-3), 284-287.

Cong WL, Pei ZJ, Van Vleet E, Wang QG (2009a) Surface roughness in rotary ultrasonic machining of stainless steels. *Proceedings of the IIE Annual Conference and Expo 2009 – Innovations Revealed*, Miami, FL, USA, May 30 - June 3.

Cong WL, Pei ZJ, Churi NJ, Wang QG (2009b) Rotary ultrasonic machining of stainless steel: design of experiments. *Transactions of the North American Manufacturing Research Institution of SME* 37, 261-268.

Cong WL, Pei ZJ, Deines T, Wang QG, Treadwell C (2010) Rotary ultrasonic machining of stainless steels: empirical study of machining variables. *International Journal of Manufacturing Research* 5 (3), 370-386.

DeVries MF, Wu SM, Mitchell JW (1967) Measurement of drilling temperature by the garter spring thermocouple method. *Microtecnic Journal* 21 (6), 583-586.

Dorr J, Mertens TH, Engering G, Lahres M (2003) 'In-situ' temperature measurement to determine the machining potential of different tool coatings. *Surface and Coatings Technology* 174-175, 389-392.

Jiao Y, Hu P, Pei ZJ, Treadwell C (2005a) Rotary ultrasonic machining of ceramics: design of experiments. *International Journal of Manufacturing Technology and Management* 7 (2-4), 192-206.

Jiao Y, Liu WJ, Pei ZJ, Xin XJ, Treadwell C (2005b) Study on edge chipping in rotary ultrasonic machining on ceramics: an integration of designed experiment and FEM analysis. *Journal of Manufacturing Science and Engineering* 127 (4), 752-758.

Kato S, Yamaguchi K, Watanabe Y, Hiraiwa Y (1976) Measurement of temperature distribution within tool using powders of constant melting point. *Journal of Engineering for Industry* 108, 607-613.

Koch U, Levi R (1971) Some mechanical and thermal aspects of twist drill performance. *Annals of the CIRP* 19 (2), 247-254.

Li R, Shih AJ (2007) Spiral point drill temperature and stress in high-throughput drilling of titanium. *International Journal of Machine Tools and Manufacture* 47 (12-13), 2005-2017.

Li ZC, Jiao Y, Deines TW, Pei ZJ, Treadwell C (2004) Experimental study on rotary ultrasonic machining (RUM) of poly crystalline diamond compacts (PDC). *Proceedings of the 13th Annual Industrial Engineering Research Conference (IERC - 2004)*, Houston, TX, USA, May 15-19.

Li ZC, Jiao Y, Deines TW, Pei ZJ, Treadwell C (2005a) Development of an innovative coolant system for rotary ultrasonic machining. *International Journal of Manufacturing Technology and Management* 7 (2-4), 318-328.

Li ZC, Pei ZJ, Zeng WM, Kwon P, Treadwell C (2005b) Preliminary experimental study of rotary ultrasonic machining on zirconia toughened alumina. *Transactions of the North American Manufacturing Research Institution of SME* 33, 89-96.

Li ZC, Jiao Y, Deines TW, Pei ZJ, Treadwell C (2005c). Rotary ultrasonic machining of ceramic matrix composites: Feasibility study and designed experiments. *International Journal of Machine Tools and Manufacture* 45 (12-13), 1402-1411.

Li ZC, Cai LW, Pei ZJ, Treadwell C (2006) Edge-chipping reduction in rotary ultrasonic machining of ceramics: finite element analysis and experimental verification. *International Journal of Machine Tools and Manufacture* 46 (12-13), 1469-1477.

Li ZC, Stanco MR, Cong WL, Pei ZJ, Xu ZG, Treadwell C (2010) Rotary ultrasonic machining of dental ceramics: a preliminary study on subsurface cracks. *Proceedings of the 2010 ASME Design of Medical Devices Conference (DMD2010)*, Minneapolis, MN, USA, April 13-15.

Lin J, Lee SL, Weng CI, (1992) Estimation of cutting temperature in high speed machining. *Journal of Engineering Material Technology* 114 (3), 289-296.

Muller-Hummel P, Lahres M (1994) Infrared measurement on diamond - coated tools during machining. *Diamond and Related Materials* 3 (4-6), 765-769.

O' Sullivan D, Cotterell M (2002) Workpiece temperature measurement in machining. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 216 (1), 135-139.

Pei ZJ, Khanna N, Ferreira PM (1995) An investigation into rotary ultrasonic machining of structural ceramics: a review. *Ceramic Engineering and Science Proceedings* 16 (1), 259-278.

Ueda T, Nozaki R, Hosokawa A (2007) Temperature measurement of cutting edge in drilling - effect of oil mist. *CIRP Annals - Manufacturing Technology* 56 (1), 93-96.

Ueda T, Sato M, Nakayama K (1998) The temperature of a single crystal diamond tool in turning. *CIRP Annals - Manufacturing Technology* 47 (1), 41-44.

Walton IM, Stephenson DJ, Baldwin A (2006) The measurement of grinding temperatures at high specific material removal rates. *International Journal of Machine Tools and Manufacture* 46 (12-13), 1617-1625.

Wang QG, Cong WL, Pei ZJ, Gao H, Kang RK (2009a) Rotary ultrasonic machining of potassium dihydrogen phosphate (KDP) crystal: an experimental investigation on surface roughness. *Journal of Manufacturing Processes* 11 (2), 66-73.

Wang QG, Pei ZJ, Gao H, Churi N, Kang RK (2009b) Rotary ultrasonic machining of potassium dihydrogen phosphate (KDP) crystal: an experimental investigation. *International Journal of Mechatronics and Manufacturing Systems* 2 (4), 414-426.

Yang X, Liu CR (1999) Machining titanium and its alloys. *Machining Science and Technology* 3 (1), 107-139.

Zeng WM, Li ZC, Pei ZJ, Treadwell C (2005) Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics. *International Journal of Machine Tools and Manufacture* 45 (12-13), 1468-1473.

Chapter 12 - CFRP - Feasibility Study

Paper title:

Rotary ultrasonic machining of CFRP: a comparison with twist drilling

Published in:

Journal of Reinforced Plastics and Composites (2012), Vol. 31, No. 5, pp. 313-321.

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Feng, Q.¹, Deines, T.W.¹, and Treadwell, C.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

2. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Drilling is involved in many applications of carbon fiber reinforced plastic (CFRP) composite. Twist drilling is widely used in industry. Rotary ultrasonic machining (RUM) has been successfully tested to drill holes in CFRP. However, there are no reports on comparisons between RUM and twist drilling of CFRP. This paper compares RUM and twist drilling of CFRP in six aspects (cutting force, torque, surface roughness, delamination, tool life, and material remove rate). Experimental results show that RUM is superior in almost all these aspects.

Keywords: Carbon fiber reinforced plastic composite, Cutting force, Rotary ultrasonic machining, Surface roughness, Tool wear, Twist drilling.

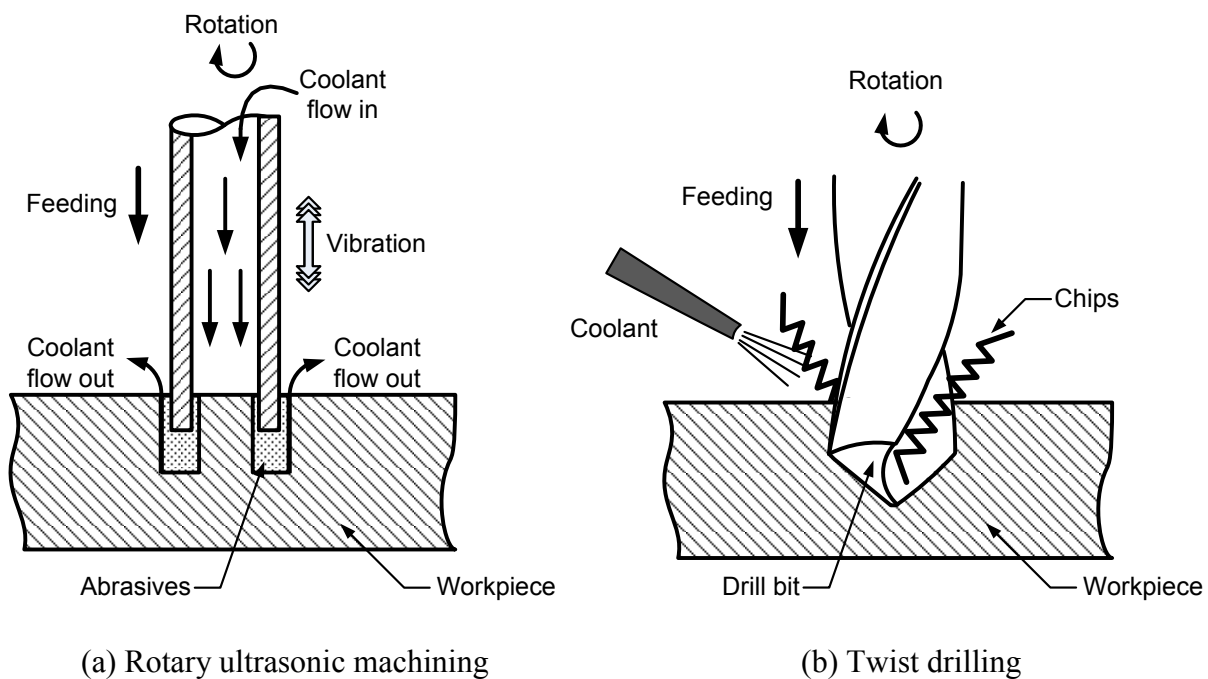
12.1 Introduction

Many applications of carbon fiber reinforced plastic CFRP composite require drilling of holes [Enemuoh et al., 2001; Tsao and Hocheng, 2005; Sprow, 1987; Chung, 2010; Gay et al., 2003]. Twist drilling and its derivate methods are widely used to produce holes in composites [Ramulu et al. 2001; Tsao and Hocheng, 2005a; Tsao and Hocheng, 2004; Campos Rubio et al., 2008; Davim and Reis, 2003b]. These methods have such shortcomings as short tool life and poor hole quality [Wong et al. 1982]. Since holes are often drilled in finished products, part rejections due to poor hole quality are very costly [Tsao and Hocheng, 2005b, Abrate and Walton, 1992].

Rotary ultrasonic machining (RUM) has been used in drilling of CFRP [Li et al., 2007, Cong et al., 2011]. RUM is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. Figure 12.1(a) illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling,

the rotating tool vibrates axially at an ultrasonic frequency and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf and prevents the tool from jamming and overheating. The literature does not have any reports on comparisons between RUM and twist drilling of CFRP. Such comparisons will be useful when deciding which process should be selected to drill holes in CFRP. This paper compares RUM and twist drilling (as illustrated in Figure 12.1(b)) of CFRP in six aspects (cutting force, torque, surface roughness, delamination, tool life, and material removal rate).

Figure 12.1 Illustration of two CFRP drilling processes.



There are four sections in this paper. Following this introduction section, Section 12.2 describes experimental conditions and measurement procedures. Section 12.3 presents and discusses experimental results. Finally, Section 12.4 provides conclusions.

12.2 Experimental conditions and measurement procedures

12.2.1 Properties of workpiece material

The CFRP workpiece was composed of carbon fibers and epoxy resin. Plain woven fabric of carbon fibers had an orientation of 0/90 degrees, as illustrated in Figure 12.2. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The workpiece contained 42 layers of carbon fibers. The size of workpiece was 200 mm × 150 mm × 16 mm. Workpiece material properties are listed in Table 12.1.

Figure 12.2 Illustration of woven fabric in CFRP.

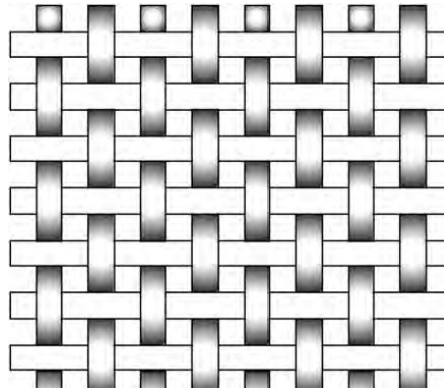


Table 12.1 Properties of workpiece material.

Property	Unit	Value
Density	kg/m ³	155
Hardness (Rockwell)	HRB	70-75
Elastic modulus of epoxy matrix	GPa	2.06 - 2.15
Tensile strength of epoxy matrix	MPa	80 - 85
Elastic modulus of carbon fiber	GPa	75 - 80
Tensile strength of carbon fiber	MPa	400 - 450

12.2.2 Experimental set-up

Twist drilling was performed on a machining center (Model VF-E, Haas Automation Inc., Oxnard, CA, USA). RUM was performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, New Mexico, USA). The RUM experimental set-up is schematically illustrated in Figure 12.3. It consisted of an ultrasonic spindle system, a data acquisition system, and a cooling system. The ultrasonic spindle system was mainly comprised of an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converted (60 Hz) electrical supply to high-frequency (20 kHz) AC output. This high frequency electrical energy was provided to a piezoelectric converter (located inside the ultrasonic spindle) that converted electrical energy into mechanical vibration. The ultrasonic vibration from the converter was amplified and transmitted to the rotary tool attached to the spindle. The amplitude of ultrasonic vibration was adjusted by changing the setting of output control of the power supply. The motor attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds were obtained by adjusting the motor speed controller. The cooling system was comprised of pump, coolant tank, pressure regulator, flow rate and pressure gauges, and valves. The cooling system provided coolant to the spindle and the interface of machining.

High speed steel twist drills (Kennametal Inc., Latrobe, PA, USA) were used in twist drilling experiments of this study. High speed steel twist drills were used in numerous reported studies on drilling CFRP [Chen, 1997; Ramulu et al., 2001; Davim and Reis, 2003; Zhang et al., 2003; Hocheng and Tsao, 2003; 2006; Kim and Ramulu, 2004; Wang et al., 2004; Tsao and Hocheng, 2004; 2005b; 2007], and would serve well as the base for comparison with RUM. A metal-bonded diamond core drill (NBR Diamond tool corp., LaGrangeville, NY, USA), as

illustrated in Figure 12.4, was used in RUM experiments. Table 12.2 contains more information on tool parameters.

Figure 12.3 RUM experimental set-up.

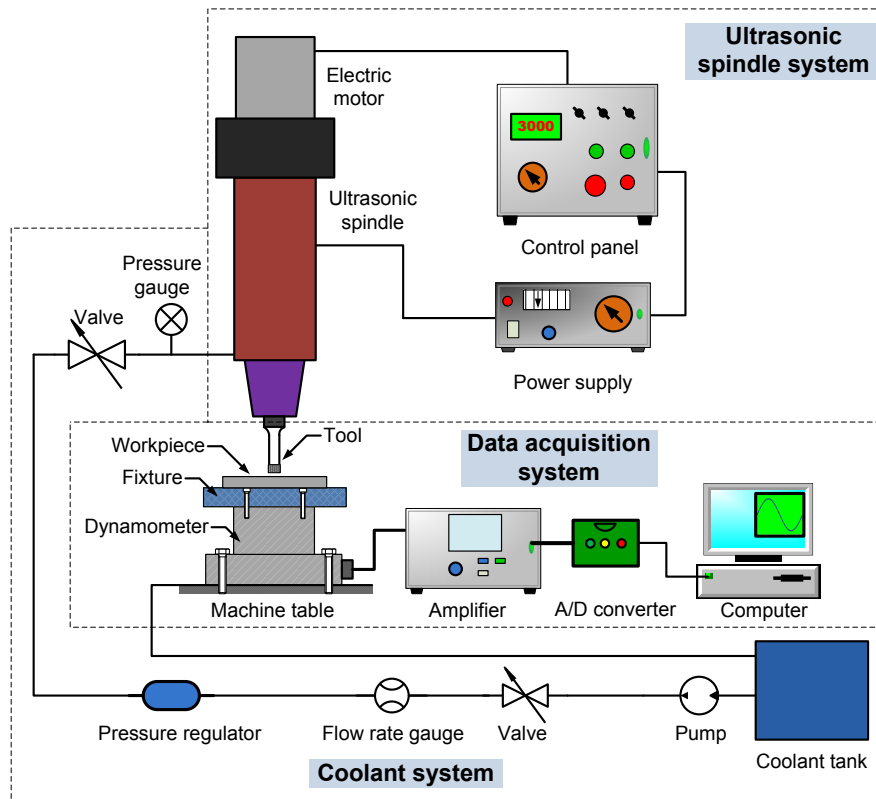


Figure 12.4 Illustration of RUM tool.

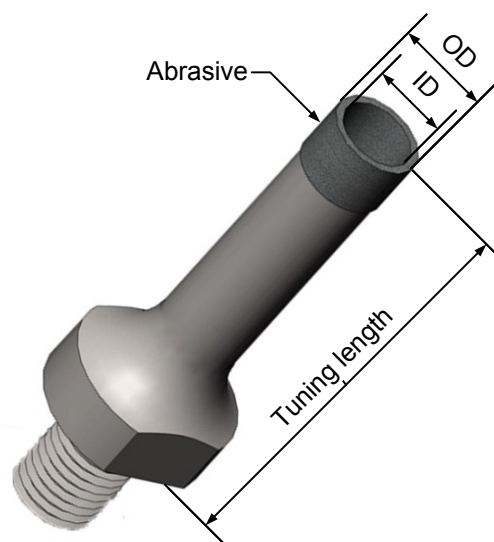


Table 12.2 Tool parameters.

Parameter	RUM tool	Twist drill
Outer diameter (mm)	9.6	9.6
Inner diameter (mm)	7.8	N/A
Tuning length/Tool length (mm)	44.5	127
Tool material	Diamond	High speed steel
Grit size (mesh #)	60/80	N/A
Grain concentration	100	N/A
Number of slots	0	N/A
Bond type	B	N/A
Point angle (°)	N/A	135

Table 12.3 Machining conditions.

Feedrate (mm/s)	Tool rotation speed (RPM)	RUM	Twist drilling
0.1	3000	√	√
0.2	3000	√	
0.3	3000	√	√
0.4	3000	√	
0.5	1000	√	
0.5	2000	√	√
0.5	3000	√	√
0.5	4000	√	√
0.5	5000	√	
0.6	3000	√	
0.7	3000	√	√
0.8	3000	√	

12.2.3 Experimental conditions

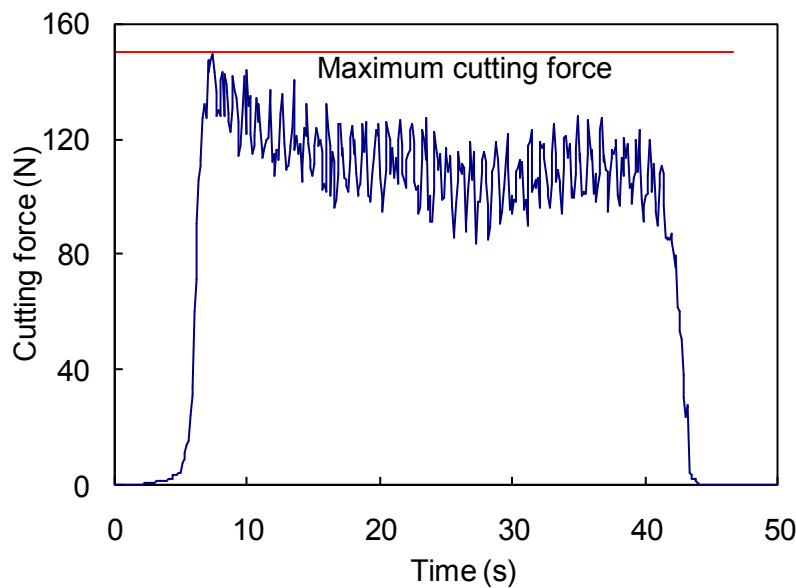
Based on experience from preliminary experiments and due to the limitations of the experimental set-ups (for example, vibration frequency was fixed at 20 kHz on the RUM machine and maximum tool rotation speed on the machining center was 4000 rpm), only two machining variables (tool rotation speed and feedrate) were changed when comparing RUM and twist drilling. Their values are shown in Table 12.3. Four holes were drilled under each machining condition.

12.2.4 Measurement procedures for output variables

A dynamometer (Model 9272, Kistler Inc., Switzerland) was used to measure the cutting force in the axial direction and torque. The electrical signals from the dynamometer were amplified by a charge amplifier (Model 5070A, Kistler Inc., Switzerland) and then transformed into digital signals by an A/D converter. After being processed by a signal conditioner, the digital signals were collected by a data acquisition card (PC-CARD-DAS16/16, Measurement Computing Corporation, Norton, MA, USA) on a computer with the help of Dynoware software (Type 2815A, Kistler Inc., Switzerland). The sampling rate was 20 Hz.

The measured cutting force fluctuated with time within a certain range. Figure 12.5 shows a typical curve of measured cutting force versus time. The maximum cutting force (F_z) on each force curve was used to represent the cutting force for drilling of each hole. Similarly, the maximum torque on the torque curve was used for drilling of each hole.

Figure 12.5 Typical relationship between cutting force and time (in RUM).



Surface roughness was measured on the surface of each machined hole. A surface profilometer (SurfTest-402, Mitutoyo Corporation, Kanagawa, Japan) was used with the tested range being set at 4 mm and the cut-off length being set at 0.8 mm. The surface roughness reported in this paper was Ra (average surface roughness). As shown in Figure 12.6, roughness was measured at a location near the hole entrance and along the axial direction of the hole. Four measurements were performed with 90° between two adjacent measurements. Each measurement was repeated twice. So for each hole, there were eight Ra values. The average of these eight values was used as the Ra value for each hole.

Figure 12.6 Illustration of surface roughness measurement.

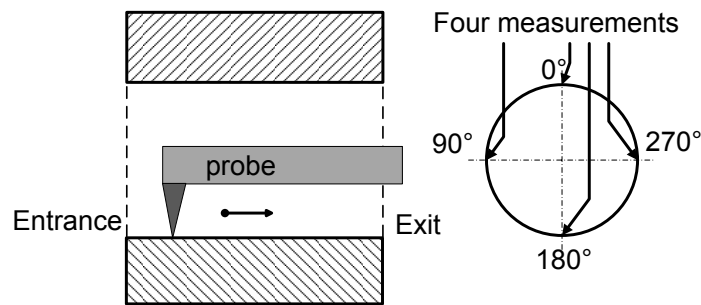
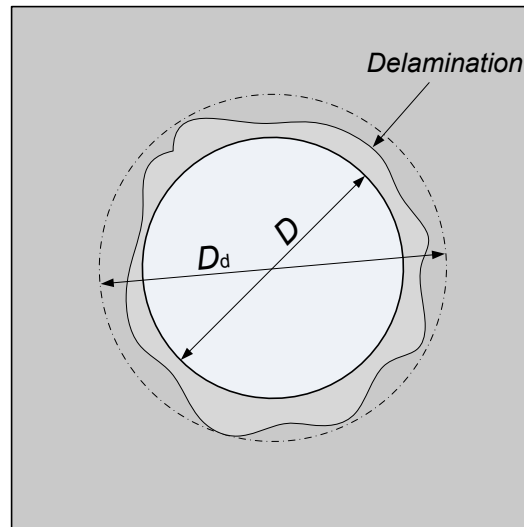


Figure 12.7 Measurement of delamination factor.



Delamination was observed sometimes on the hole drilled in composite materials. Delamination factor [Tsao and Hocheng, 2004] was used to describe the degree of delamination. It was determined by D_d/D . Figure 12.7 illustrates both D_d and D . D is the hole diameter. D_d is the diameter of the smallest circle that encloses all the delamination area around the hole. D_d and D were measured by a vernier caliper (model IP-65, Mitutoyo Corp., Kanagawa, Japan).

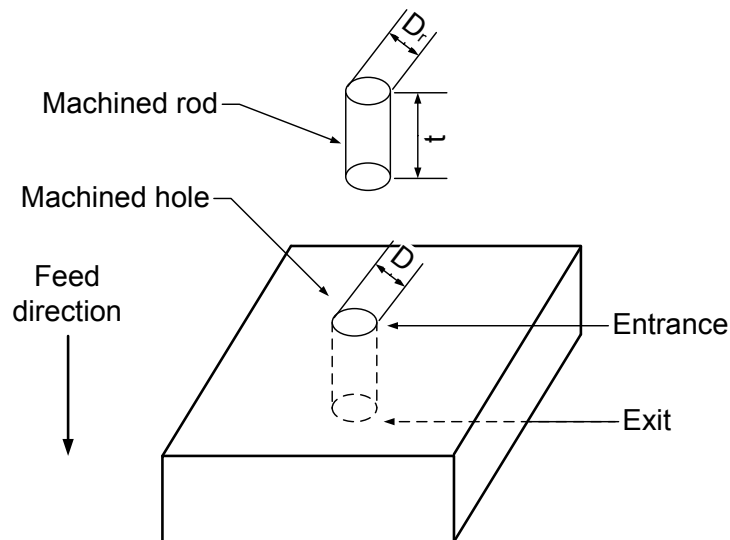
Material removal rate (MRR) was calculated as the volume of material removed divided by machining time. It can be expressed by following equations:

$$\text{MRR} = \frac{\pi \cdot [(D/2)^2 - (D_r/2)^2] \cdot h}{T} \quad (\text{for RUM}) \quad (12.1)$$

$$\text{MRR} = \frac{\pi \cdot (D/2)^2 \cdot h}{T} \quad (\text{for twsit drilling}) \quad (12.2)$$

where, D is the diameter of machined hole, h is the thickness of workpiece, T is the time it takes to drill the hole, and D_r is the diameter of machined rod (only applicable to RUM). Figure 12.8 illustrates the machined hole and rod in RUM. D_r was also measured by a vernier caliper (model IP-65, Mitutoyo Corp., Kanagawa, Japan).

Figure 12.8 Illustration of the hole and rod machined by rotary ultrasonic machining.



12.3 Experimental results

12.3.1 Cutting force

Figure 12.9 shows a comparison of cutting force between RUM and twist drilling when tool rotation speed changed. In Figure 12.9 (as well as Figure 12.10 – Figure 12.16), the data points are the average values from four holes drilled under the same condition. Error bars represent the maximum and minimum values from all four holes. For both RUM and twist drilling, cutting force decreased with the increase of tool rotation speed. However, cutting forces in RUM were much lower. When tool rotation speed was 2000 rpm, cutting force in twist drilling was nearly five times of that in RUM. The change of cutting force in RUM was very small when tool rotation speed increased from 1000 to 5000 rpm.

Figure 12.9 Cutting force comparison between RUM and twist drilling when tool rotation speed changed.

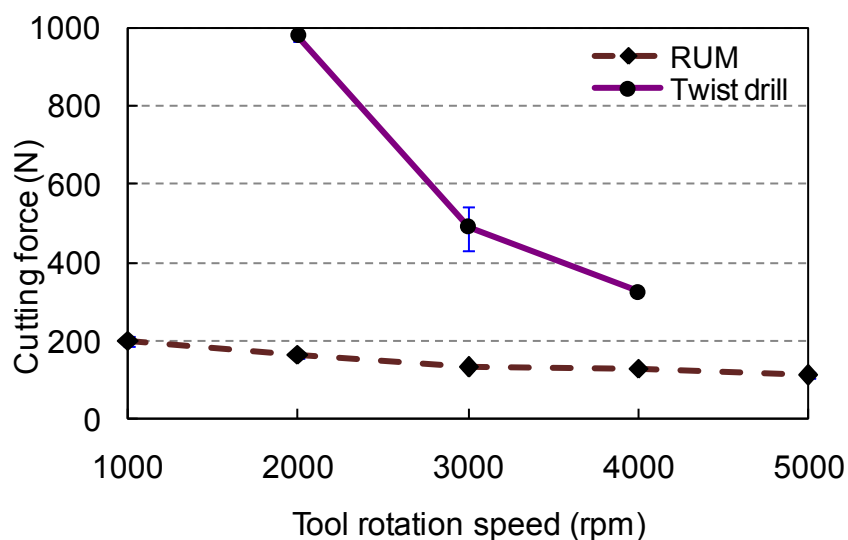
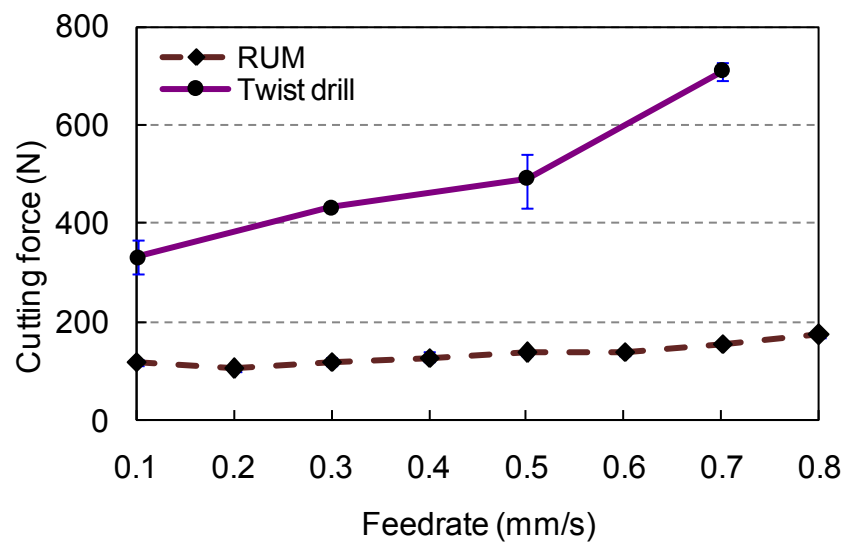


Figure 12.10 shows a comparison of cutting force between RUM and twist drilling when feedrate changed. At all levels of feedrate, cutting forces in twist drilling were much higher than those in RUM. With the increase of feedrate, cutting force increased for both RUM and twist drilling. However, when feedrate increased from 0.1 to 0.8 mm/s, the change of cutting force in RUM was very small, less than 100 N. In contrast, the change of cutting force in twist drilling was much larger.

Figure 12.10 Cutting force comparison between RUM and twist drilling when feedrate changed.



12.3.2 Torque

Figure 12.11 shows a comparison of torque between RUM and twist drilling when tool rotation speed changed. When tool rotation speed increased, torque in both RUM and twist drilling decreased. Torques in twist drilling were larger than those in RUM when tool rotation speeds were 2000, 3000, and 4000 rpm. Tool rotation speed had larger effects on torque in twist drilling than in RUM. In RUM, the change of torque was very small (about 0.2 N·m) when tool

rotation speed increased from 1000 to 5000 rpm. In twist drilling, the change of torque was 0.6 N·m when tool rotation speed increased from 2000 to 4000 rpm.

Figure 12.11 Torque comparison between RUM and twist drilling when tool rotation speed changed.

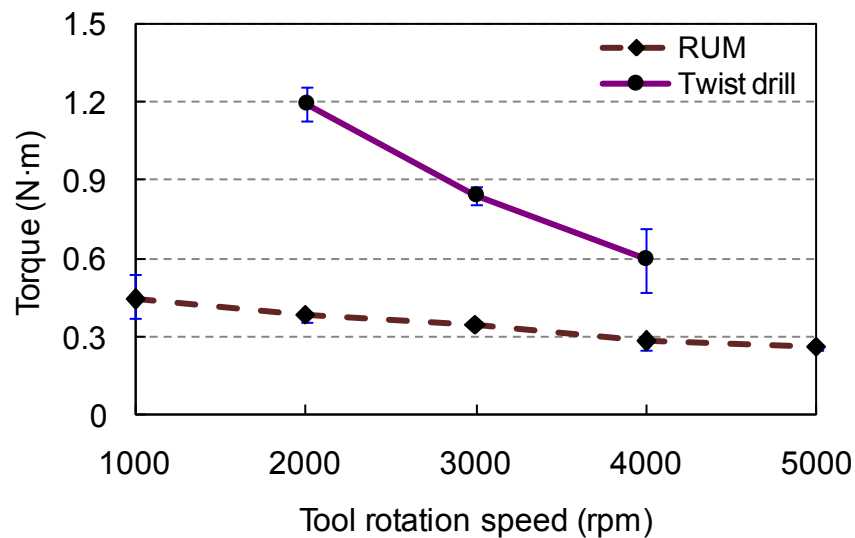
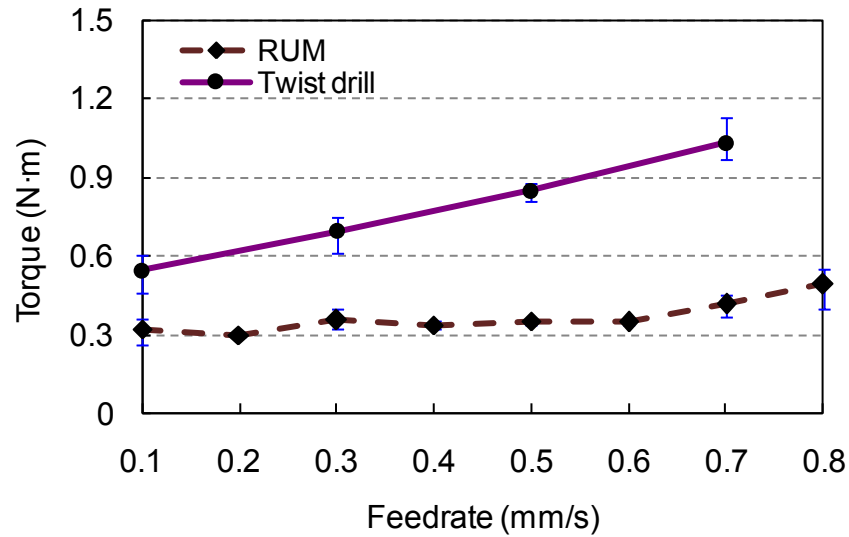


Figure 12.12 shows a comparison of torque between RUM and twist drilling when feedrate changed. With the increase of feedrate, torque increased in both RUM and twist drilling. At all levels of feedrate, torques in twist drilling were larger than those in RUM. When feedrate increased from 0.1 to 0.7 mm/s, torque in twist drilling increased almost linearly from 0.6 to 1.0 N·m. In contrast, the change of torque in RUM was only 0.2 N·m when feedrate changed from 0.1 to 0.8 mm/s.

Figure 12.12 Torque comparison between RUM and twist drilling when feedrate changed.



12.3.3 Surface roughness

A comparison of surface roughness between RUM and twist drilling when tool rotation speed changed is shown in Figure 12.13. Surface roughness in twist drilling was higher than that in RUM. When tool rotation speed increased, surface roughness decreased in both RUM and twist drilling, but the change of surface roughness in RUM was smaller.

A comparison of surface roughness between RUM and twist drilling when feedrate changed is shown in Figure 12.14. In both RUM and twist drilling, surface roughness of drilled holes increased with the increase of feedrate. However, the magnitudes of changes were different. In twist drilling, surface roughness increased remarkably with the increase of feedrate. In contrast, surface roughness in RUM increased moderately. At all levels of feedrate, surface roughness in twist drilling was higher than that in RUM.

Figure 12.13 Surface roughness comparison between RUM and twist drilling when tool rotation speed changed.

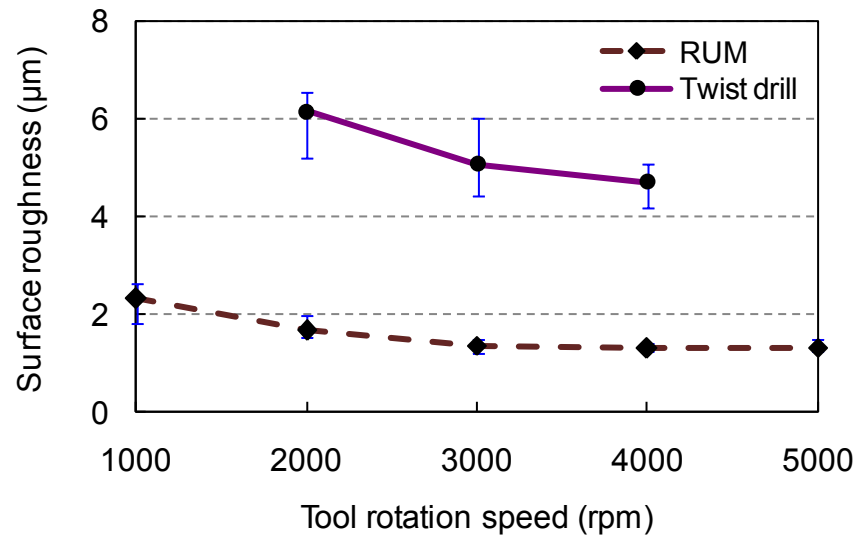
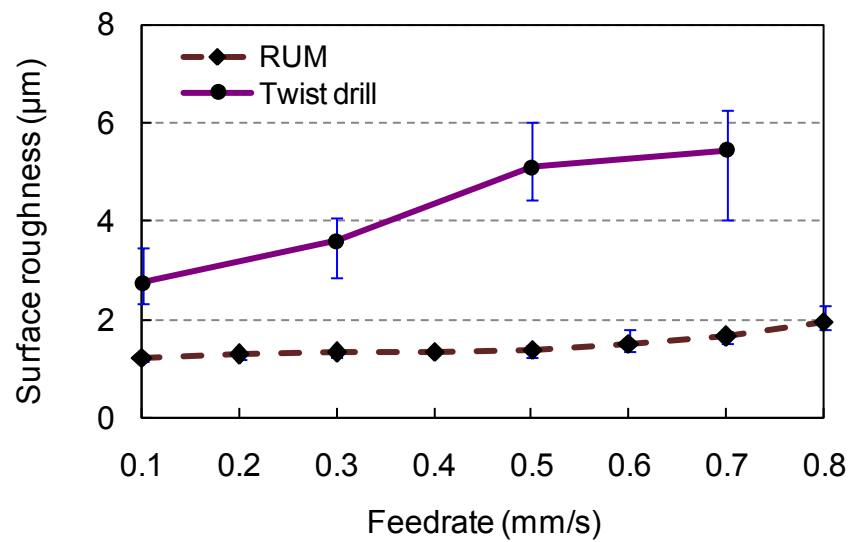


Figure 12.14 Surface roughness comparison between RUM and twist drilling when feedrate changed.



12.3.4 Delamination

No delamination could be observed in RUM of CFRP under all the conditions tested.

The change of delamination in twist drilling when tool rotation speed changed is shown in Figure 12.15. When tool rotation speed changed from 2000 to 3000 rpm, delamination factor decreased from about 1.4 to 1.3. However, delamination factor did not change much with further increase of tool rotation speed (from 3000 to 4000 rpm).

The change of delamination in twist drilling when feedrate changed is shown in Figure 12.16. When feedrate changed from 0.1 to 0.7 mm/s, delamination factor increased almost linearly from about 1.2 to 1.4.

Figure 12.15 Effects of tool rotation speed on delamination factor in twist drilling.

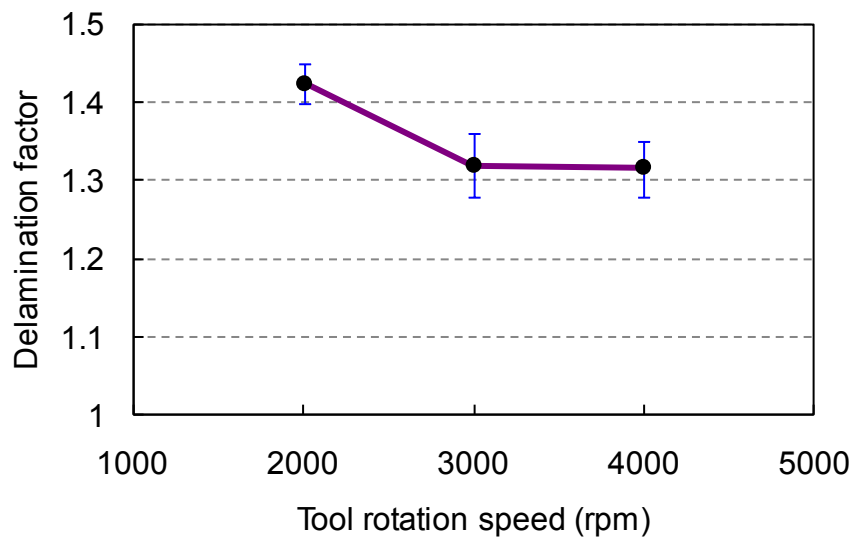
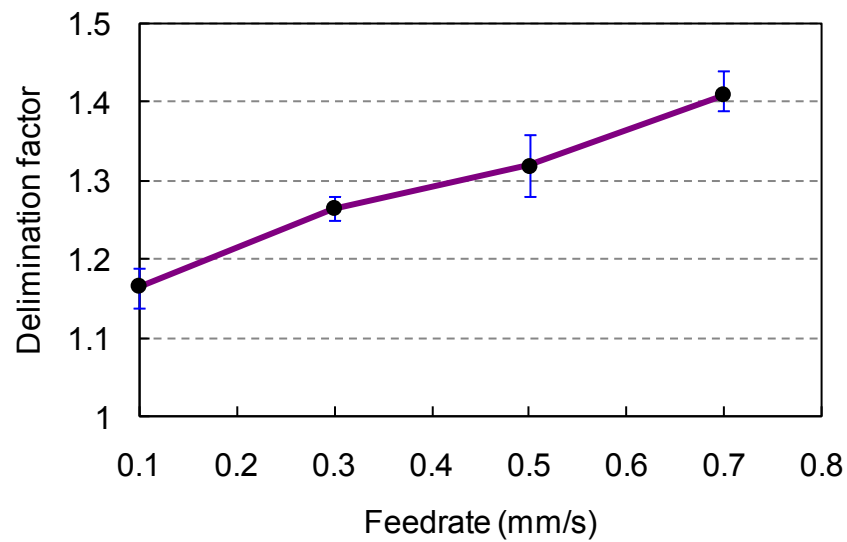


Figure 12.16 Effects of feedrate on delamination factor in twist drilling.



12.3.5 Tool life

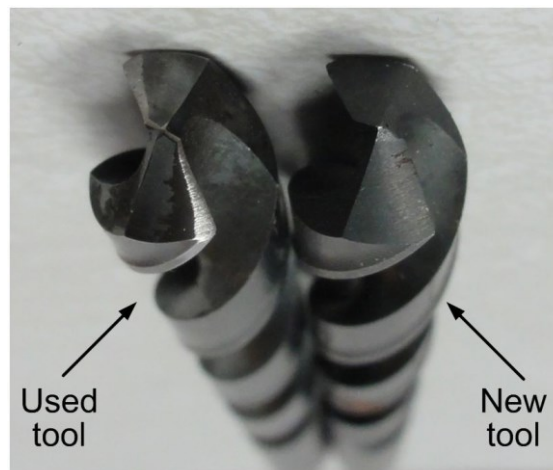
Figure 12.17 shows pictures of a brand new tool and a used tool in RUM. It can be seen that the used tool was shorter than the new one. The used tool had been used to drill more than 200 holes and its abrasive portion decreased by 0.9 mm in length. At this wear rate, one tool with 7 mm length of abrasive portion can drill more than 1400 holes.

Figure 12.18 shows pictures of a brand new tool and a used tool in twist drilling. Cutting edges of the twist drill were worn out after drilling only five holes.

Figure 12.17 A new RUM tool and a used RUM tool after drilling more than 200 holes.



Figure 12.18 A new twist drill and a used twist drill after drilling five holes.



12.3.6 Material removal rate (MRR)

Figure 12.19 shows a comparison of MRR between RUM and twist drilling when tool rotation speed changed. It can be seen that tool rotation speed had no effects on MRR. At all levels of tool rotation speed, MRR remained constant for both RUM and twist drilling. However, MRR in twist drilling was higher than that in RUM.

A comparison of MRR between RUM and twist drilling when feedrate changed is shown in Figure 12.20. In both RUM and twist drilling, MRR increased linearly with the increase of feedrate. However, the rates of increasing were not the same. When feedrate changed from 0.1 to 0.7 mm/s, MRR in twist drilling increased by 18 mm³/s (from 3 to 21 mm³/s), but MRR in RUM increased by only 3.5 mm³/s. In addition, the values of MRR in twist drilling were higher than those in RUM. This is because the machined rod was not included when calculating MRR in RUM. It is noted that holes with the same diameter (9.6 mm) were produced in both RUM and twist drilling, although MRR values were very different. However, if the rod is included in its calculation, MRR in RUM will be the same as that in twist drilling.

Figure 12.19 Material removal rate comparison between RUM and twist drilling when tool rotation speed changed.

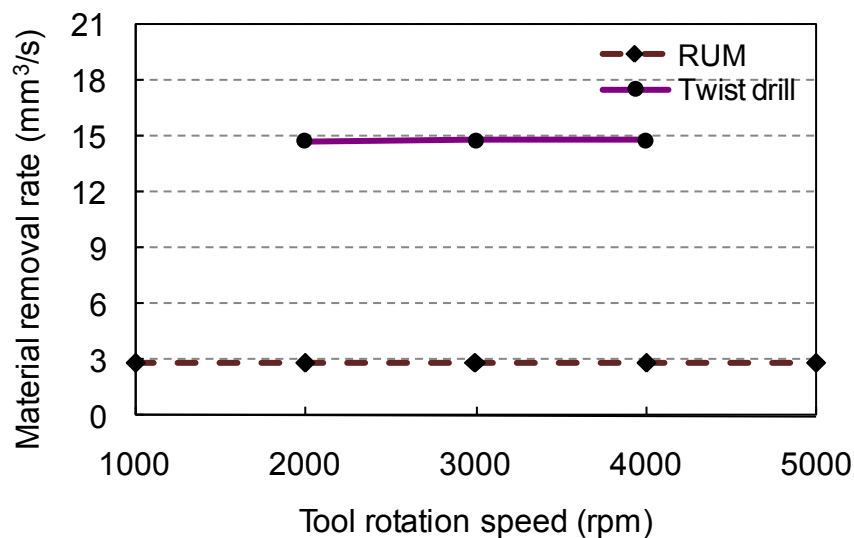
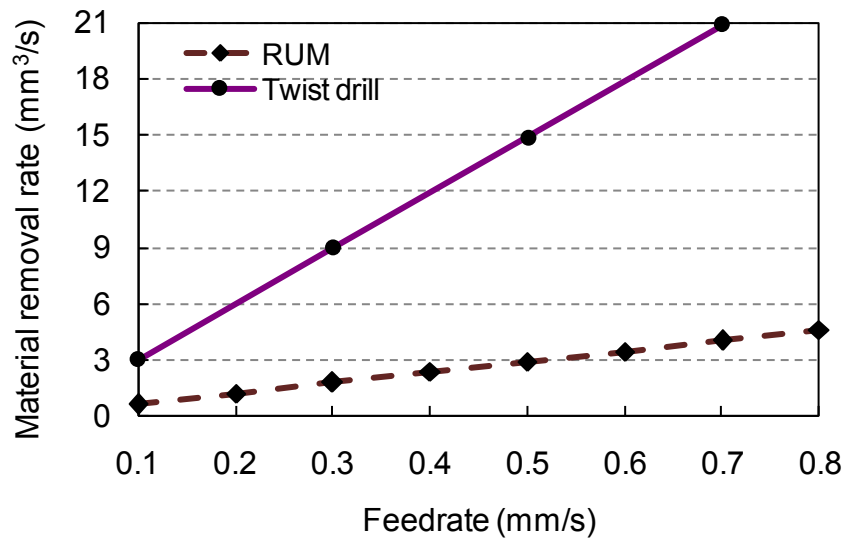


Figure 12.20 Material removal rate comparison between RUM and twist drilling when feedrate changed.



12.4 Conclusions

This paper reported a comparison study on twist drilling and rotary ultrasonic machining RUM of CFRP. Cutting force, torque, surface roughness, delamination, tool life, and material removal rate were compared. The following conclusions are drawn from this study:

- (a) Cutting force and torque in twist drilling were higher than those in RUM.
- (b) Surface roughness in twist drilling was higher than that in RUM.
- (c) The holes machined by RUM did not show any delamination. In twist drilling, delamination decreased as tool rotation speed increased or feedrate decreased.
- (d) Tool life in RUM was much longer than in twist drilling. A new RUM tool could drill more than 1400 holes while a new twist drill could drill only five holes before wearing out.
- (e) Twist drilling had higher material removal rate than RUM under the same conditions when holes with the same diameter were produced.

RUM is a diamond grinding process assisted with ultrasonic vibration. The cutting tool contains metal-bonded diamond abrasives, and is much more effective in machining CFRP, especially the carbon fibers inside CFRP. Therefore, in comparison with twist drilling of CFRP (for a hole with the same size and within the same duration of time), RUM has lower cutting force and torque, better surface roughness, no delamination, and longer tool life.

Acknowledgements

The work was supported by National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to Mr. Bruno Renzi at N.B.R. Diamond tool Corp. for supplying the diamond core drill.

References

- [1] Abrate, S., and Walton D.A., 1992, Machining of composite materials. Part I: Traditional method, *Composites Manufacturing*, 3(2), pp. 75-83.
- [2] Arul, S., Vijayaraghavan, L., Malhotra, S.K., and Krishnamurthy, R., 2006, The effect of vibratory drilling on hole quality in polymeric composites, *International Journal of Machine Tools and Manufacture*, 46(3-4), pp. 252-259.
- [3] Barbero, E.J., 2011, *Introduction to Composite Materials Design*, 2nd edition, CRC press, Boca Raton, FL, USA.
- [4] Campos Rubio, J.C., Abrão, A.M., Eustáquio Faria, P., Correia, A.E., and Davim, J.P., 2008, Delamination in high speed drilling of carbon fiber reinforced plastic (CFRP), *Journal of Composite Materials*, 42(15), pp. 1523-1532.

- [5] Chen, W.C., 1997, Some experimental investigation in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates, *International Journal of Machine Tools and Manufacture*, 37(8), pp. 1097-1108.
- [6] Chung, D.D.L., 2010, *Composite Materials Science and Applications*, 2nd edition, Springer London Ltd, London, UK.
- [7] Cong, W.L., Feng, Q., Pei, Z.J., Deines, T.W., and Treadwell, C., 2011, Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables, submitted to ASME 2011 International Manufacturing Science and Engineering Conference.
- [8] Davim, J.P., and Reis, P., 2003a, Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, *Materials and Design*, 24(5), pp. 315-324.
- [9] Davim, J.P., Reis, P., 2003b, Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments, *Composite Structures*, 59(4), pp. 481-487.
- [10] Enemuoh, E.U., El-Gizawy, A.S., and Okafor, A.C., 2001, An approach for development of damage-free drilling of carbon fiber reinforced thermosets, *International Journal of Machine Tools and Manufacture*, 41(12), pp. 1795-1814.
- [11] Illescu, D., Gehin, D., Gutierrez, M.E., and Girot, F., 2010, Modeling and tool wear in drilling of CFRP, *International Journal of Machine Tools & Manufacture*, 50(2), pp. 204-213.
- [12] Gay, D., Hoa, S.V., and Tsai, S.W., 2003, *Composite Materials Design and Applications*, 4th edition, CRC press, Boca Raton, FL, USA.
- [13] Guu, Y.H., Hocheng, H., Tai, N.H., and Liu, S.Y., 2001, Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, *Journal of*

- Materials Science, 36(8), pp. 2037-2043.
- [14] Hocheng, H., and Tsao, C.C., 2003, Comprehensive analysis of delamination in drilling of composite materials with various drill bits, *Journal of Materials Processing Technology*, 140(1-3), pp. 335-339.
- [15] Hocheng, H., and Tsao, C.C., 2006, Effect of special drill bits on drilling-induced delamination of composite materials, *Journal of Machine Tools and Manufacture*, 46(12-13), pp. 1403-1416.
- [16] Kim, D., and Ramulu, M.R., 2004, Drilling process optimization for graphite/bismaleimide-titanium alloy stacks, *Composite Structures*, 63(1), pp. 101-114.
- [17] Lambert, B.K., 1987, Cutting and drilling of composite materials, *The Carbide and Tool Journal*, 19(5), pp. 31-34.
- [18] Lee, D.G., Sin, H.C., and Suh, N.P., 1985, Manufacturing of a graphite epoxy composite spindle for a machine tool, *CIRP Annals 1985: Manufacturing Technology*, Paris, France, 34(1), pp. 365-369.
- [19] Li, Z.C., Pei, Z.J., Sisco, T., Micale, A.C. and Treadwell, C., 2007, Experimental study on rotary ultrasonic machining of graphite/epoxy panel, *Proceedings of the ASPE 2007 Spring Topical Meeting on Vibration Assisted Machining Technology*, Chapel Hill, NC, April 16-17, pp. 52-57.
- [20] Mallick, P.K., 1997, *Composite Engineering Handbook*, Marcel Dekker Inc, New York, NY, USA.
- [21] Ramulu M., Branson T., and Kim D., 2001, A study on the drilling of composite and titanium stacks, *Composite Structure*, 54(1), pp. 67-77.
- [22] Ruegg, C.H., and Habermeier, J., 1981, *Composite propeller shafts: design and*

- optimization, *Automotive Engineer*, 6(3), pp. 13-15.
- [23] Sadat, A.B., 1995, Delamination and other types of damage of graphite/epoxy composite caused by machining, *Applied Mechanics Division and the Materials Division: Machining of Advanced Materials*, Los Angeles, CA, June 28-30, pp. 41-52.
- [24] Schwartz, M.M., 1992, *Composite Materials Handbook*, 2nd edition, McGraw-Hill, Columbus, OH, USA.
- [25] Sprow, E.E., 1987, Cutting composite: Three choices for any budget, *Tooling & Production*, 43(12), pp. 46-50.
- [26] Tsao, C.C., and Hocheng, H., 2004, Taguchi analysis of delamination associated with various drill bits in drilling of composite material, *International Journal of Machine Tools and Manufacture*, 44(10), pp. 1085-1090.
- [27] Tsao, C.C., and Hocheng, H., 2005a, Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials, *International Journal of Machine Tools and Manufacture*, 45(2), pp. 125-130.
- [28] Tsao, C.C., and Hocheng, H., 2005b, Computerized tomography and C-Scan for measuring delamination in the drilling of composite materials using various drills, *International Journal of Machine Tools and Manufacture*, 45(11), pp. 1282-1287.
- [29] Tsao, C.C., and Hocheng, H., 2007 Effect of tool wear on delamination in drilling composite materials, *International Journal of Mechanical Sciences*, 49(8), pp. 983-988.
- [30] Wang, X., Wang, L.J., and Tao, J.P., 2004, Investigation on thrust in vibration drilling of drilling of fiber-reinforced plastics, *Journal of Materials Processing Technology*, 148(2), pp. 239-244.
- [31] Wong, T.L., Wu, S.M. and Croy, G.M., 1982, An analysis of delamination in drilling

composite materials, Proceedings 14th SAMPLE Technology Conference, Atlanta, GA, USA.

- [32] Zhang, L.B., Wang, L.J., and Wang, X., 2003, Study on vibration drilling of fiber reinforced plastics with hybrid variation parameters method, Composites: Part A, 34(3), pp. 237-244.

Chapter 13 - CFRP - Dry Drilling

Paper title:

Rotary ultrasonic machining of carbon fiber reinforced plastic composites: using cutting fluid versus cold air as coolant

Published in:

Journal of Composite Materials (2012), Vol. 46, No. 14, pp. 1745-1753.

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Feng, Q.¹, Deines, T.W.¹, and Treadwell, C.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

2. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Drilling is involved in many applications of carbon fiber reinforced plastic (CFRP) composites. Rotary ultrasonic machining (RUM) has been successfully employed to drill holes in CFRP using either cutting fluid or cold air as coolant. However, there are no reported studies to compare the results in RUM of CFRP using these two types of coolant. This paper, for the first time, presents an experimental study to compare cutting force, torque, surface roughness, burning of machined surface, and tool wear in RUM of CFRP using these two types of coolant. This study will result in knowledge about machining conditions under which it is feasible to use cold air instead of cutting fluid and differences in machined hole quality produced using cold air versus cutting fluid.

Keywords: Dry machining, Carbon fiber reinforced plastic composite, Rotary ultrasonic machining, Cold air, Vortex tube.

13.1 Introduction

CFRP composites have high strength to weight ratios [Davim and Reis, 2003, Lambert, 1987; Sadat, 1995; Guu et al., 2001], low density [Chung, 2010], superior stiffness to weight ratios [Davim and Reis, 2003; Guu et al., 2001], strong tailorability [Chung, 2010], high damping ability [Chung, 2010], low thermal expansion [Mallick, 1997; Schwartz, 1992], high service temperatures [Guu et al., 2001], and high chemical (corrosion) resistance [Chung, 2010]. These properties cannot be obtained from conventional metals such as steel and aluminum [Mallick, 1997; Schwartz, 1992]. CFRP composites are attractive for many applications due to these superior properties. They are used in many types of structures including aircraft, spacecraft, automobile, ship, bridge, athletic equipment, and leisure goods. They are also employed in engine blades, power transmission shafts, machine spindles, robot arms, pressure vessels, and

chemical containers [Park et al., 1995; Ruegg and Habermeier, 1981; Gay et al., 2003; Guu et al., 2001; Arul et al., 2006; Sadat, 1995].

Many applications of carbon fiber reinforced plastic (CFRP) composites require machining [Enemuoh et al., 2001; Chung, 2010; Gay et al., 2003], including milling [Hashmi et al., 2009; De Lacalle et al., 2009] and drilling. Twist drilling is widely used to produce holes in CFRP [Rubio et al., 2008; Gaitonde et al., 2008; Ramulu et al. 2001; Tsao and Hocheng, 2004; 2005; 2007; Davim and Reis, 2003; Hocheng et al., 2003; 2006]. Rotary ultrasonic machining (RUM) has also been successfully used to drill holes in CFRP [Li et al., 2007; Cong et al., 2011ab]. RUM is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. A rotating core drill with metal-bonded diamond abrasives vibrates ultrasonically in its axial direction and feeds towards the workpiece. Coolant (cutting fluid or cold air) goes through the core of the drill to wash out swarfs and keeps cutting temperature low. Compared with twist drilling, RUM has many advantages, such as smaller cutting force, lower surface roughness, less tool wear, and less delamination. An experimental investigation to compare twist drilling and RUM using the same workpiece material and similar machining conditions has been conducted by the authors. Results of the investigation will be published in a separate paper.

Cutting fluids help to remove the heat generated during machining; to achieve better tool life, surface finish, and dimensional tolerance; to prevent the formation of built-up edge; and to facilitate the transportation of chips [Sreejith and Ngoi, 2000]. However, cutting fluids also have several disadvantages. First, deployment of cutting fluids counts for about 7-17% of the total cost of machining. As a comparison, costs of tool only account for approximately 2-4% [Klock and Eisenblatter, 1997]. Moreover, treatment of waste cutting fluids also has considerable costs.

Second, one of the major concerns is the health and environment hazard associated with cutting fluids [Arumugam et al., 2006].

Dry machining (machining without direct contact between coolant fluid and cutting zone) can avoid the problems related to cutting fluids. However, dry machining can potentially cause burning of machined surface, more friction and adhesion between tool and workpiece, reduction of tool life, and high surface roughness [Liu and Hu, 1997; Sreejith and Ngoi, 2000; Nguyen and Zhang, 2003].

Reported experimental investigations [Li et al., 2007; Cong et al., 2011ab] on RUM of CFRP employed either cutting fluid or cold air as coolant. However, there are no reported studies to compare the results in RUM of CFRP using these two types of coolant. This paper, for the first time, presents an experimental study to compare cutting force, torque, surface roughness, burning of machined surface, and tool wear in RUM of CFRP using these two types of coolant.

13.2 Experimental conditions and measurement procedures

The workpiece size was 200 mm $\times$ 150 mm $\times$ 16 mm. The workpiece material was carbon fiber reinforced plastic (CFRP) composites. It was composed of carbon fibers and epoxy resin. Plain woven fabric of carbon fibers had an orientation of 0/90 degrees. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The workpiece contained 42 layers of carbon fibers. Workpiece material properties are listed in Table 13.1.

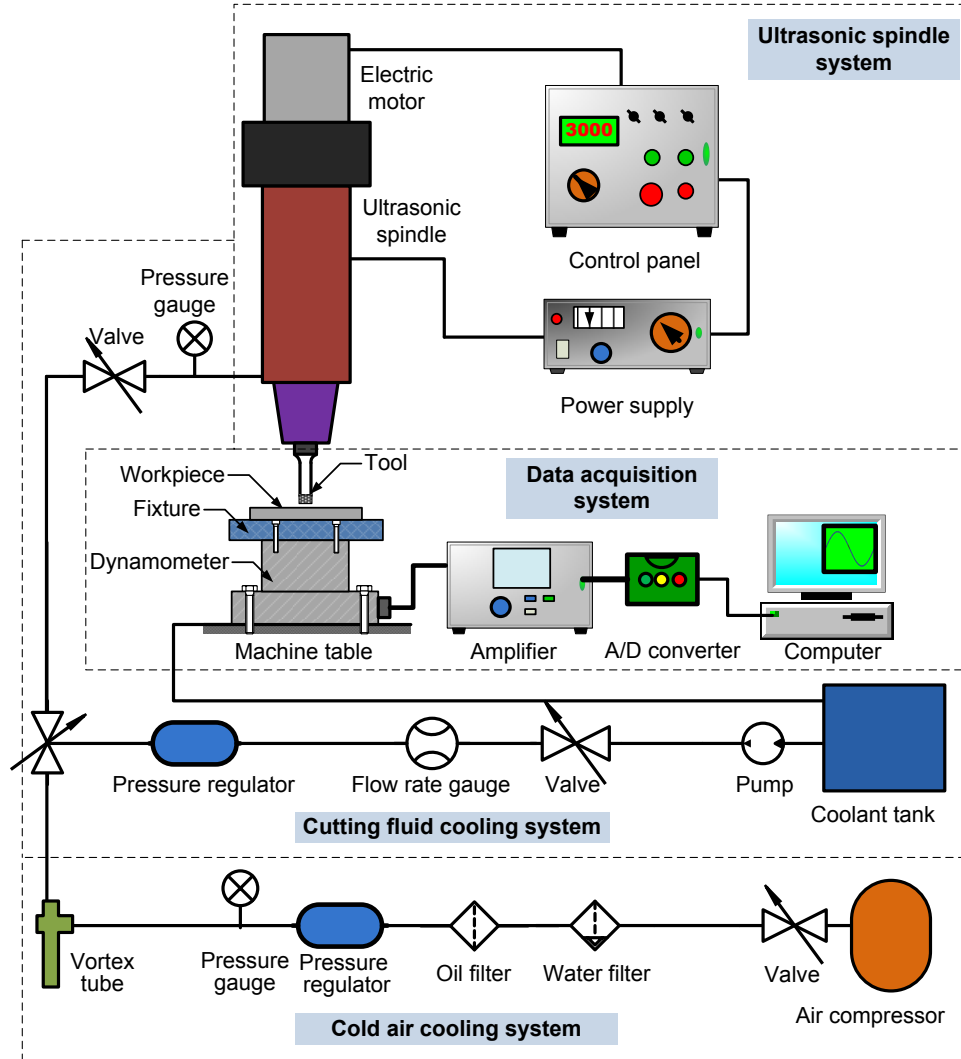
Drilling experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 13.1. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a cooling system. The ultrasonic spindle system was comprised of an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converted conventional line voltage to 20 kHz

electrical energy. This high-frequency electrical energy was provided to a piezoelectric converter that changed high-frequency electrical energy into mechanical vibration. The ultrasonic vibration was amplified and transmitted to the cutting tool. This caused the cutting tool to vibrate at the frequency of 20 kHz. The amplitude of ultrasonic vibration could be adjusted by changing the setting of output control of the power supply. The motor attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds could be obtained by adjusting the motor speed controller. The data acquisition system, including dynamometer, charge amplifier, A/D convertor, and computer with software, was used for measurement of cutting force and torque. More details about this system will be described in Section 2.4 (measurement procedures). There were two separate cooling systems: cutting fluid cooling system and cold air cooling system. The cutting fluid cooling system was comprised of pump, coolant tank, pressure regulator, flow rate and pressure gauges, and valves. The cold air cooling system included air compressor, oil and water filter, pressure regulator and valve, vortex tube, and pressure meters. The cooling system provided coolant (cutting fluid or cold air) to the spindle and the interface of machining.

Table 13.1 Properties of workpiece material.

Property	Unit	Value
Density	kg/m ³	155
Hardness (Rockwell)	HRB	70-75
Elastic modulus of epoxy matrix	GPa	2.06 - 2.15
Tensile strength of epoxy matrix	MPa	80 - 85
Elastic modulus of carbon fiber	GPa	75 - 80
Tensile strength of carbon fiber	MPa	400 - 450

Figure 13.1 Experimental set-up.



In this study, the cold air was generated by a vortex tube (VT). The VT separated a stream of compressed air into a hot and a cool branch. Hot air came out of one end of the tube and cold air out of the other [Ahlborn et al., 1994; Liu and Chou, 2005 & 2007; AiRTX 2010; Hilsch, 1947; Cong et al., 2008]. The cutting fluid (Quakercool 6010, Murdock Industrial Supply Co., Wichita, KS, USA) was of water-soluble type.

Metal-bonded diamond core drills (NBR Diamond Tool Corp., LaGrangeville, NY, USA) were used. The outer and inner diameters (OD and ID) of the drills were 9.54 mm and 7.82 mm,

respectively, and the tuning length was 45 mm. The diamond abrasives had mesh size of 60/80 and concentration of 100. The metal bond was of B type.

Following input variables were varied in the experiments:

- Spindle speed: Rotational speed of core drill;
- Feedrate: Feedrate of core drill;
- Ultrasonic power: Percentage of power from ultrasonic power supply (higher ultrasonic power would produce higher ultrasonic vibration amplitude);
- Coolant type: Cutting fluid or cold air.

The pressure and flow rate for both cutting fluid and cold air were kept the same at 40 psi and 1.5 lpm, respectively. The input variables and their values are shown in Table 13.2. Four holes were drilled under each machining condition to study cutting force, torque, surface roughness, and burning of machined surface.

Table 13.2 Input variables and their values.

Variable	Value
Ultrasonic power (%)	0; 20; 40; 60; 80
Tool rotation speed (rpm)	1000; 2000; 3000; 4000; 5000
Feedrate (mm/s)	0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.7; 0.8
Cold air pressure (psi)	40
Cold air flow rate (lpm)	1.5
Cold air temperature (°C)	-3 ± 2

A dynamometer (Model 9272, Kistler Inc., Switzerland) was used to measure the cutting force and torque. The electrical signals from the dynamometer were amplified by a charge amplifier (Model 5070A, Kistler Inc., Switzerland) and transformed into digital signals by an A/D converter. After being processed by a signal conditioner, the digital signals were saved on a computer by a data acquisition card (PC-CARD-DAS16/16, Measurement Computing

Corporation, Norton, MA, USA) with the help of DynoWare software (Type 2815A, Kistler Inc., Switzerland). The sampling rate was set at 20 Hz. The maximum cutting force in the tool axial direction during the entire period of time to drill a hole was used as the cutting force for drilling the hole. Similarly, the maximum torque was used as the torque for drilling the hole.

Surface roughness was measured on the cylindrical surfaces of machined holes along the axial direction. A surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan) was used with the test range being set as 4 mm and the cut-off length as 0.8 mm. The surface roughness in this study was characterized by Ra, average surface roughness. Roughness was measured at two locations of the hole: entrance and exit. At each location, four measurements were performed with 90° between two adjacent measurements. Each measurement was repeated four times. Therefore, at each location, there were eight measured Ra values. The average of these eight Ra values was used as the Ra value for the location.

During machining, the epoxy matrix could be burned under certain conditions due to machining-induced heat. Burning ratio $\left(= \frac{\text{Burning area on machined hole surface}}{\text{Total area of machined hole surface}} \right)$ was used to describe the severity of burning on the machined hole surface. In the paper, burning ratio was estimated by the ratio between the number of fiber layers that had burning and the number of fiber layers that had no burning.

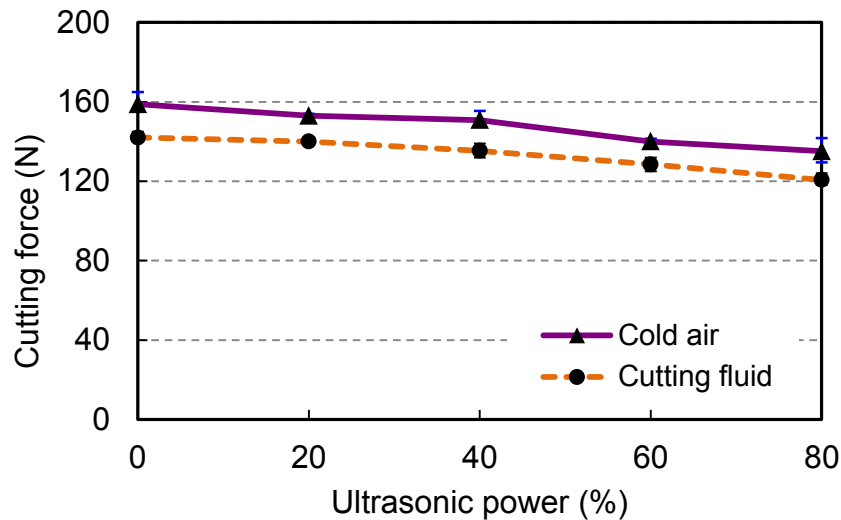
Tool wear was evaluated using the weight loss of the tool (using the weight of the tool prior to the tests as the reference). Before weight measurement, the tool was cleaned (using methanol and acetone) and dried (using a hand dryer). The tool weight was measured by a high-accuracy scale (Model APX-200, Denver Instrument, Denver, CO, USA).

13.3 Experimental results

13.3.1 Results on cutting force

Figure 13.2 shows a comparison of cutting force between the two types of coolant under different settings of ultrasonic power. In Figure 13.2 (as well as Figure 13.3 – Figure 13.11), each data point is the average value for the four holes drilled under that condition. Error bars represent the minimum and maximum values among the four holes. It can be seen that, for both types of coolant, cutting force decreased with the increase of ultrasonic power. When ultrasonic power increased from 0% to 80%, the decrease of cutting force was about 20 N for both types of coolant. Using cold air resulted in larger cutting force. The difference in cutting force between these two types of coolant did not change much when ultrasonic power changed. Cold air did not have the lubricating effect that cutting fluid had, resulting in larger cutting force.

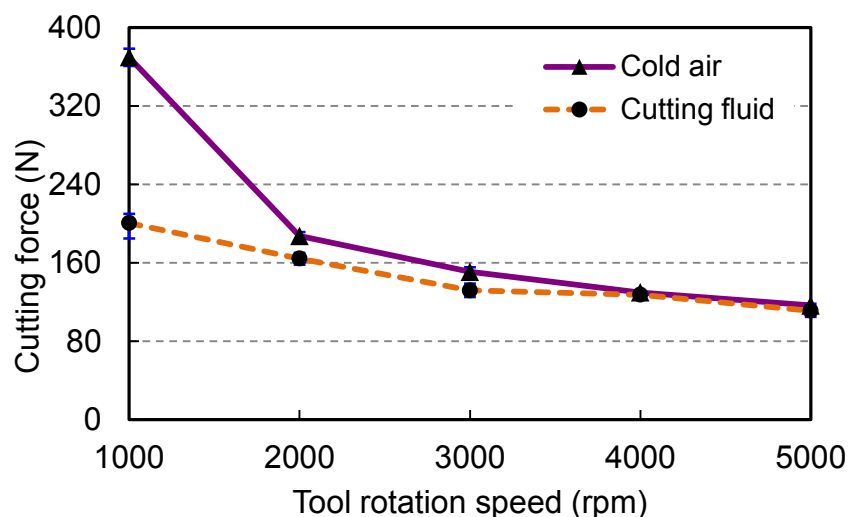
Figure 13.2 Comparison of cutting force under different settings of ultrasonic power.



Tool rotation speed = 3000 rpm
Feedrate = 0.5 mm/s

A comparison of cutting force between the two types of coolant under different settings of tool rotation speed is shown in Figure 13.3. Cutting force decreased with the increase of tool rotation speed for both types of coolant. When tool rotation speed was between 1000 and 3000 rpm, using cold air led to larger cutting force. When tool rotation speed was between 4000 and 5000 rpm, cutting force was about the same for both types of coolant. Cutting force in RUM of CFRP (as well as titanium, stainless steel, alumina, and silicon carbide) was determined by the interaction force between diamond grains on the drill end surface and the workpiece material. This interaction force was affected by the penetration depth of diamond grains into the workpiece material. As tool rotation speed increased, the penetration depth of diamond grains into the workpiece material would decrease (since the feedrate was kept the same). This would reduce the interaction force between diamond grains and the workpiece material, hence reducing cutting force.

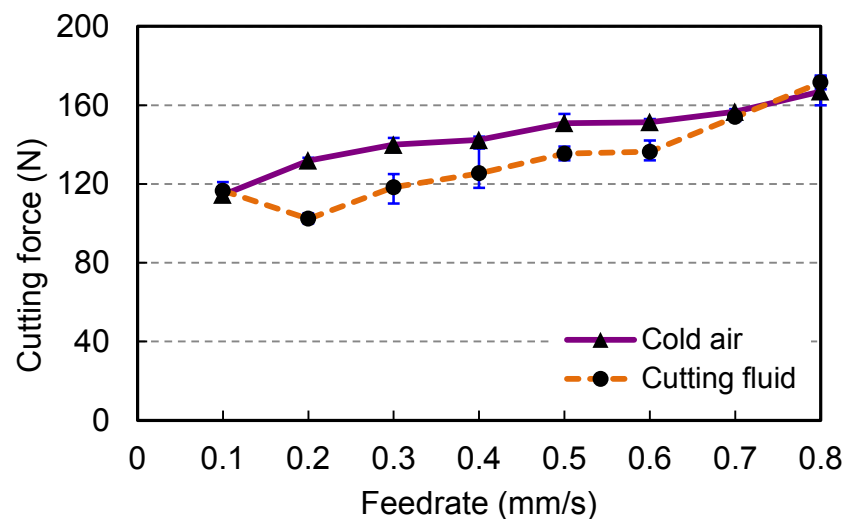
Figure 13.3 Comparison of cutting force under different settings of tool rotation speed.



Ultrasonic power = 40%
Feedrate = 0.5 mm/s

A comparison of cutting force between the two types of coolant under different settings of feedrate is shown in Figure 13.4. With the increase of feedrate, cutting force increased for both types of coolant. At some feedrate settings (such as 0.1, 0.7, and 0.8 mm/s), cutting force was about the same for both types of coolant. At other feedrate settings (from 0.2 to 0.6 mm/s), using cold air resulted in larger cutting force. As feedrate increased, the penetration depth of diamond grains into the workpiece material would increase. This would increase the interaction force between diamond grains and the workpiece material, hence increasing cutting force.

Figure 13.4 Comparison of cutting force under different settings of feedrate.



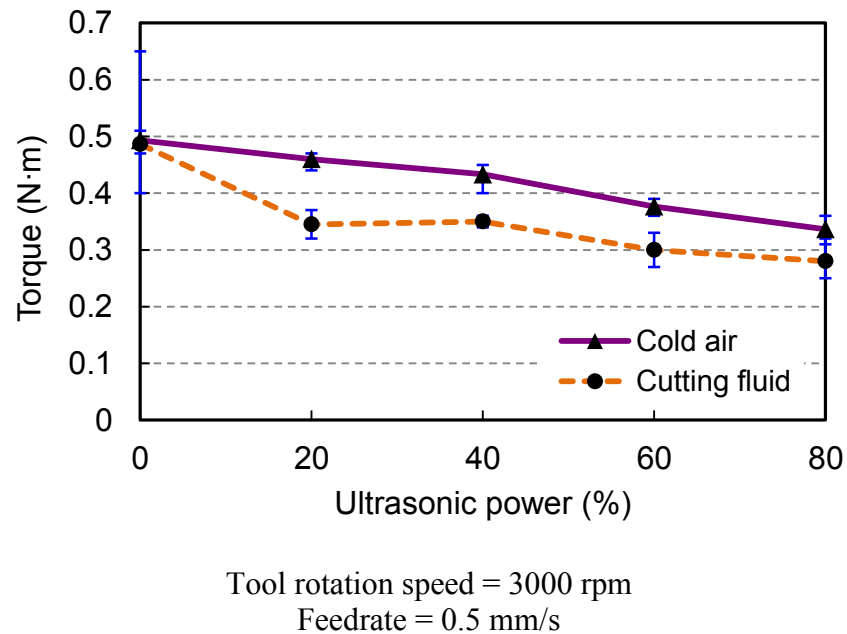
Ultrasonic power = 40%
Tool rotation speed = 3000 rpm

13.3.2 Results on torque

Figure 13.5 shows a torque comparison between the two types of coolant under different settings of ultrasonic power. Torque decreased with the increase of ultrasonic power for both types of coolant. The torque was about 0.5 N·m for both types of coolant when ultrasonic power was 0 (without ultrasonic vibration). When ultrasonic power was between 20% and 80%, using

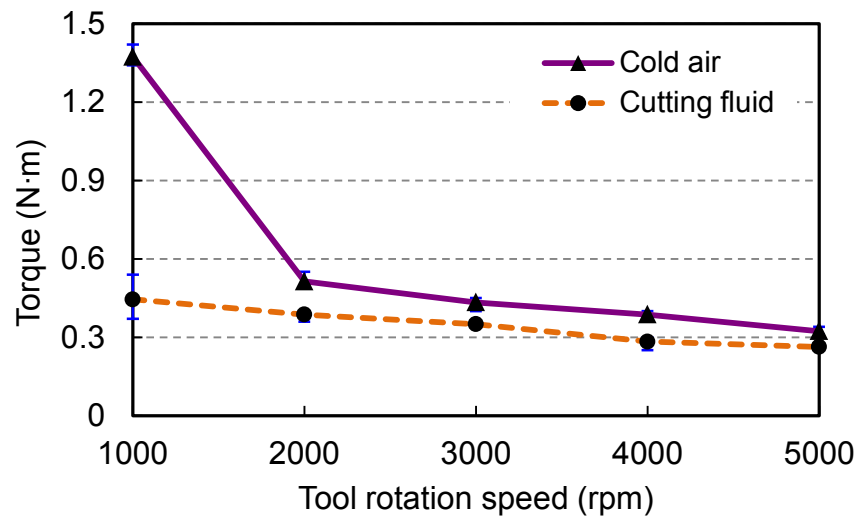
cold air had larger torque than using cutting fluid. The trends of cutting force and torque as ultrasonic power increased were the same. The reason for larger torque with cold air was similar to that for larger cutting force with cold air.

Figure 13.5 Comparison of torque under different settings of ultrasonic power.



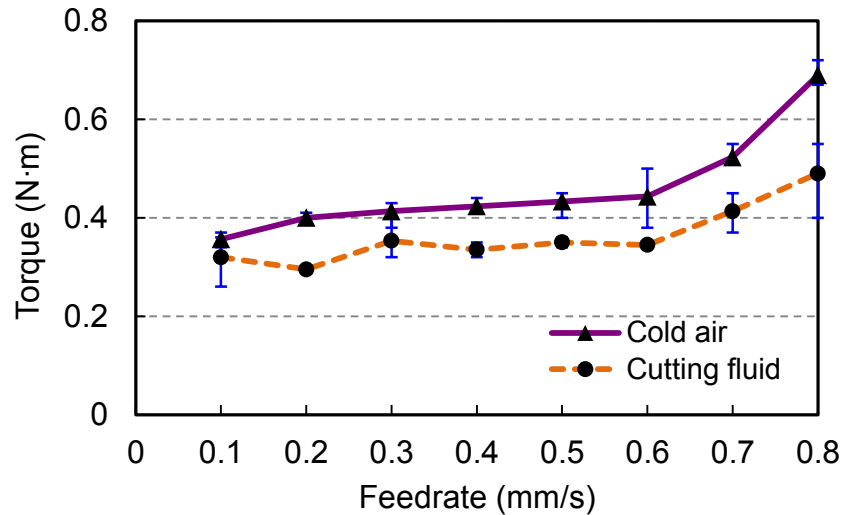
A comparison of torque between the two types of coolant under different settings of tool rotation speed is shown in Figure 13.6. With the increase of tool rotation speed, torque decreased for both types of coolant. Using cold air led to larger torque than using cutting fluid. When tool rotation speed was 1000 rpm, using cold air had much larger torque (1.4 N·m) than using cutting fluid (0.45 N·m). When tool rotation speed was between 2000 and 5000 rpm, using cold air led to slightly larger torque than using cutting fluid. This trend was similar to that of cutting force.

Figure 13.6 Comparison of torque under different settings of tool rotation speed.



Ultrasonic power = 40%
Feedrate = 0.5 mm/s

Figure 13.7 Comparison of torque under different settings of feedrate.



Ultrasonic power = 40%
Tool rotation speed = 3000 rpm

Figure 13.7 shows a torque comparison between the two types of coolant under different settings of feedrate. It can be seen that torque increased with the increase of feedrate for both

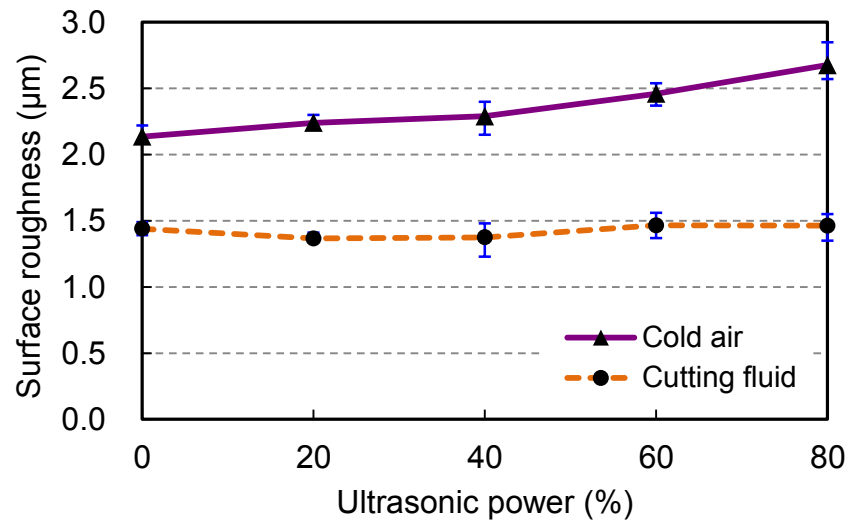
types of coolant. Using cold air led to larger torque than using cutting fluid. When feedrate increased from 0.1 to 0.6 mm/s, the increase of torque was slow for both types of coolant. However, when feedrate increased from 0.6 to 0.8 mm/s, the increase of torque became fast for both types of coolant. Again, cutting force and torque had a similar trend as feedrate increased.

13.3.3 Results on surface roughness

A comparison of surface roughness between the two types of coolant under different settings of ultrasonic power is shown in Figure 13.8. As the entrance location, as shown in Figure 13.8(a), with the increase of ultrasonic power, surface roughness increased when using cold air, but did not change much when using cutting fluid. Using cutting fluid led to lower surface roughness at all settings of ultrasonic power. At the exit location, as shown in Figure 13.8(b), surface roughness and ultrasonic power did not have monotonous relationship for both types of coolant. Surface roughness when using cutting fluid was lower than that when using cold air at all settings of ultrasonic power. The lubricating effect of cutting fluid would result in lower surface roughness.

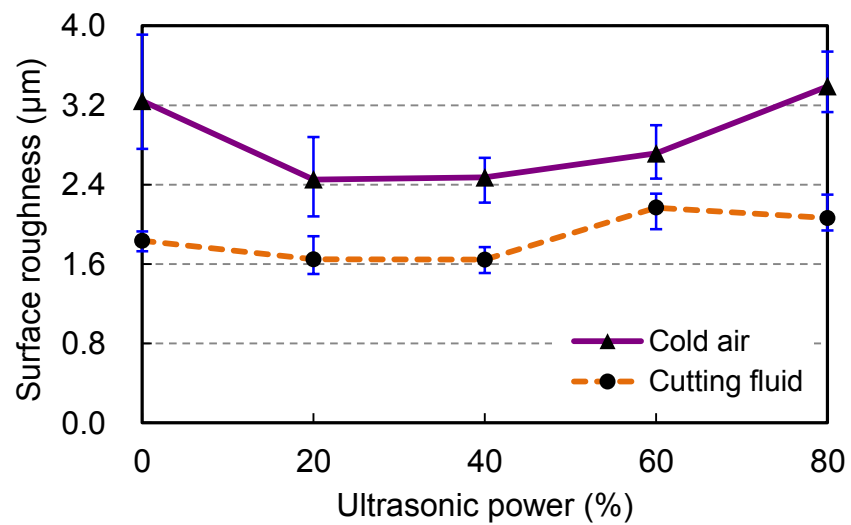
Figure 13.9 shows a comparison of surface roughness between the two types of coolant under different settings of tool rotation speed. Surface roughness decreased as tool rotation speed increased for both types of coolant. The reason could be that, as tool rotation speed increased, the linear cutting speed increased. At all settings of tool rotation speed, surface roughness when using cutting fluid was lower than that when using cold air. When tool rotation speed was between 1000 and 2000 rpm, using cold air led to higher surface roughness. This was because severe surface burning happened in RUM of CFRP using cold air when tool rotation was low (1000 or 2000 rpm). When tool rotation speed was between 3000 and 5000 rpm, surface roughness had similar values for both types of coolant.

Figure 13.8 Comparison of surface roughness under different settings of ultrasonic power.



Tool rotation speed = 3000 rpm; Feedrate = 0.5 mm/s

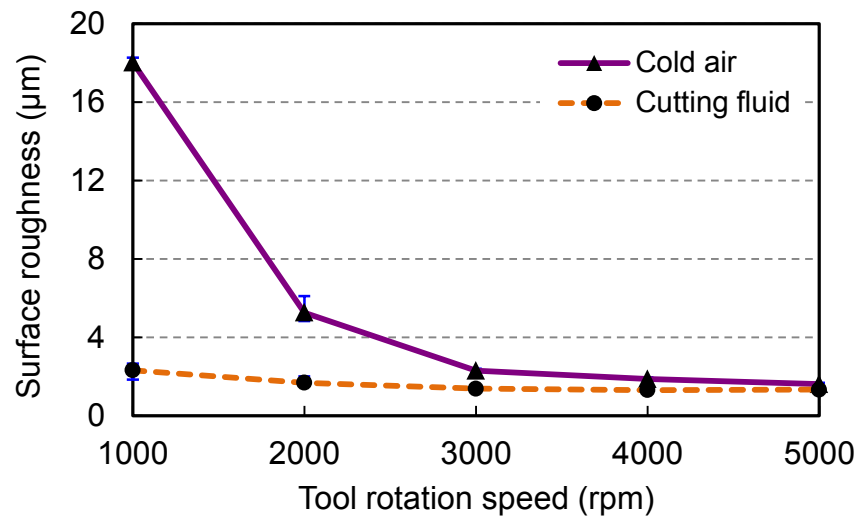
(a) at the entrance location



Tool rotation speed = 3000 rpm; Feedrate = 0.5 mm/s

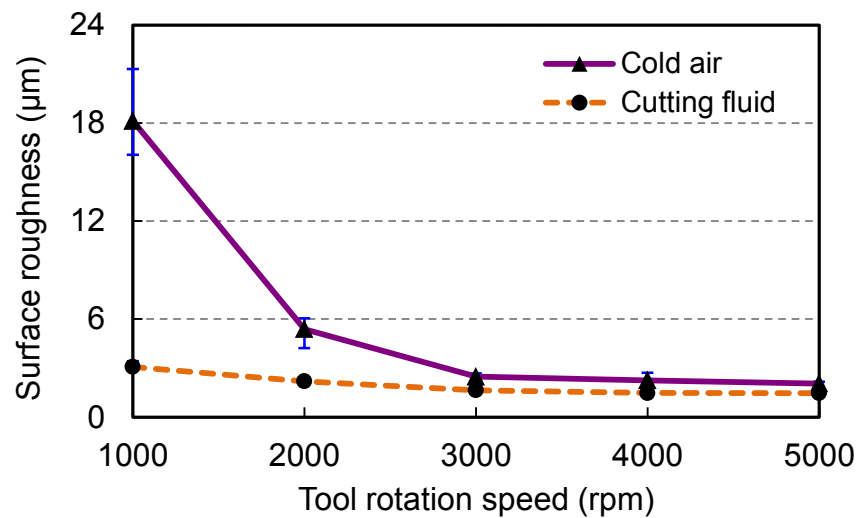
(b) at the exit location

Figure 13.9 Comparison of surface roughness under different settings of tool rotation speed.



Ultrasonic power = 40%; Feedrate = 0.5 mm/s

(a) at the entrance location



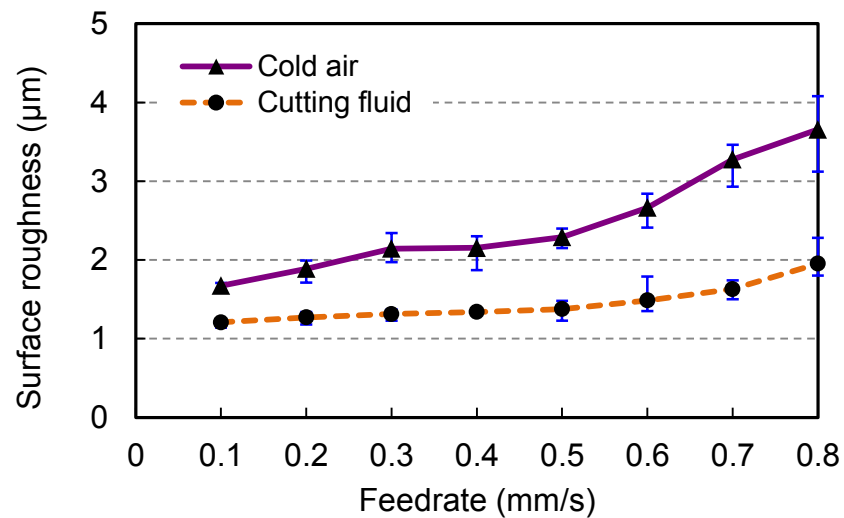
Ultrasonic power = 40%; Feedrate = 0.5 mm/s

(b) at the exit location

Figure 13.10 shows a comparison of surface roughness between the two types of coolant under different settings of feedrate. For both types of coolant, surface roughness increased with the increase of feedrate. At all settings of feedrate, surface roughness when using cold air was

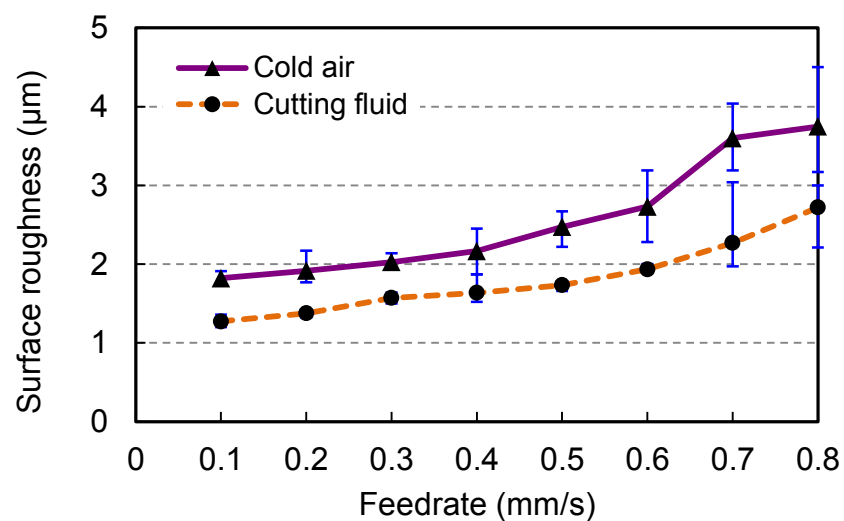
higher than that when using cutting fluid. With the increase of feedrate, the difference in surface roughness between the two types of coolant became larger.

Figure 13.10 Comparison of surface roughness under different settings of feedrate.



Ultrasonic power = 40%; Tool rotation speed = 3000 rpm

(a) at the entrance location



Ultrasonic power = 40%; Tool rotation speed = 3000 rpm

(b) at the exit location

13.3.4 Results on burning of machined surface

Burning of machined surface did not occur when using cutting fluid under any of the test conditions. In contrast, burning occurred when using cold air under some conditions. Tables 13.3-13.5 show the results on burning ratio when using cold air.

Table 13.3 Effects of ultrasonic power on burning ratio using cold air.

Feedrate (mm/s)	Ultrasonic power (%)				
	0	20	40	60	80
0.1	0	0	0	0	10%
0.5	0	0	0	0	0

*Tool rotation speed = 3000 rpm.

Table 13.4 Effects of tool rotation speed on burning ratio using cold air.

Feedrate (mm/s)	Tool rotation speed (rpm)				
	1000	2000	3000	4000	5000
0.1	0	0	0	0	0
0.5	90%	50%	0	0	0

*Ultrasonic power = 40%.

Table 13.5 Effects of feedrate on burning ratio using cold air.

Feedrate (mm/s)							
0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
0	0	0	0	0	0	10%	20%

*Ultrasonic power = 40%; Tool rotation speed = 3000 rpm.

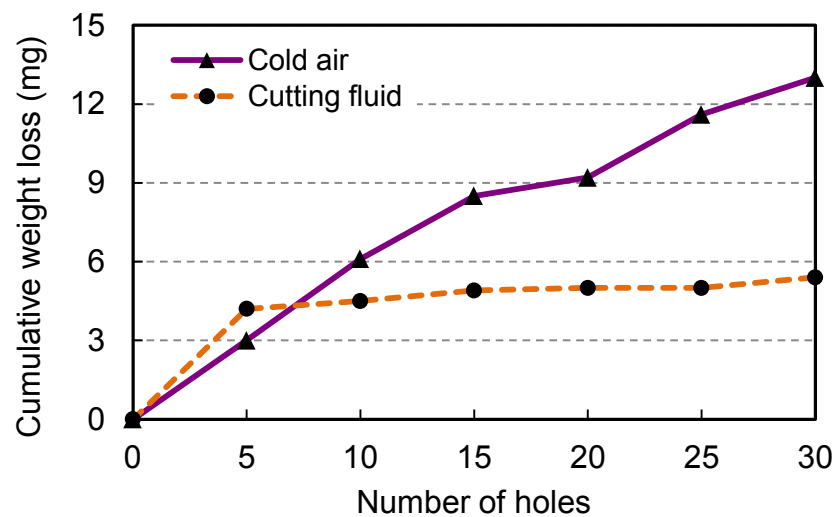
Table 13.3 shows effects of ultrasonic power on burning ratio. When feedrate was 0.1 mm/s, higher ultrasonic power (80%) caused burning of machined surface. When feedrate was 0.5 mm/s, burning did not occur no matter what ultrasonic power was. Table 13.4 shows effects of tool rotation speed on burning ratio. When feedrate was 0.5 mm/s, burning ratio became

higher as tool rotation speed decreased (to 1000 or 2000 rpm). When feedrate was 0.1 mm/s, burning did not occur no matter what tool rotation speed was. Table 13.5 shows effects of feedrate on burning ratio. Burning ratio became higher when feedrate was too high (0.7 and 0.8 mm/s).

13.3.5 Results on tool wear

Figure 13.11 compares tool wear (i.e. cumulative tool weight loss) between the two types of coolant. For the first ten holes, both types of coolant had similar tool wear. After ten holes, as more holes were drilled, tool wear increased steadily when using cold air, but did not change much when using cutting fluid. Differences in tool weight loss between the two types of coolant increased as more holes were drilled. After 30 holes were drilled, the difference was around 8 mg.

Figure 13.11 Comparison of tool wear.



Ultrasonic power = 40%;
Tool rotation speed = 3000 rpm;
Feedrate = 0.5 mm/s

13.4 Conclusions

This paper reported a comparison study on rotary ultrasonic machining of CFRP using two types of coolant: cutting fluid versus cold air. Cutting force, torque, surface roughness, burning of machined surface, and tool wear have been compared under different settings of machining variables. The following settings of conclusions are drawn from this study:

- (a) Using cold air led to larger cutting force and torque than using cutting fluid under most conditions. However, under some conditions, cutting force or torque values were about the same for both types of coolant.
- (b) Surface roughness using cold air was usually higher than that using cutting fluid.
- (c) Using cold air, higher ultrasonic power, lower tool rotation speed, and higher feedrate could lead to more severe burning of machined surface. In contrast, no burning of machined surface was observed using cutting fluid.
- (d) Tool wear when using cold air was more severe than that when using cutting fluid.

Acknowledgements

The work was supported by the National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to Mr. Bruno Renzi at N.B.R. Diamond Tool Corp. for supplying the diamond core drills. Thanks also go to Mr. Eric Zinke and Mr. Jeffrey Wilbert, undergraduate students in the Department of Industrial and Manufacturing Systems Engineering, Kansas State University, for their help during this study.

References

- [1] Ahlborn, B., Keller, J.U., Staudt, R., Treitz, G., and Rebhan, E., 1994, Limits of temperature separation in a vortex tube, *Journal of Physics D: Applied Physics*, 27(3), pp. 480-488.
- [2] AiRTX, 2010, How Vortex Tubes Work, Company Web site, available at: <http://www.airtxinternational.com/vortex-tubes/>.
- [3] Arul, S., Vijayaraghavan, L., Malhotra, S.K., and Krishnamurthy, R., 2006, The effect of vibratory drilling on hole quality in polymeric composites, *International Journal of Machine Tools and Manufacture*, 46(3-4), pp. 252-259.
- [4] Arumugam, P.U., Malshe, A.P., and Batzer, S.A., 2006, Dry machining of aluminum-silicon alloy using polished CVD diamond-coated cutting tools inserts, *Surface and Coating Technology*, 200(11), pp. 3399-3403.
- [5] Chung, D.D.L., 2010, *Composite Materials Science and Applications*, Second edition, Springer-Verlag London Ltd., London, UK.
- [6] Cong, W.L., and Pei, Z.J., 2008, Dry machining using vortex-tube generated cold air as coolant: a literature review, *Proceedings of the ASME International Manufacturing Science and Engineering Conference*, October 7-10, Evanston, IL, USA.
- [7] Cong, W.L., Feng, Q., Pei, Z.J., Deines, T., and Treadwell, C., 2011a, Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables, *Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference*, June 13-17, Corvallis, OR, USA.
- [8] Cong, W.L., Feng, Q., Pei, Z.J., Deines, T., and Treadwell, C., 2011b, Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions, accepted to appear in

Journal of Reinforced Plastics and Composites.

- [9] Davim, J.P., and Reis, P., 2003, Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, *Materials and Design*, 24(5), pp. 315-324.
- [10] De Lacalle, L.N.L., Lamikiz, A., Campa, F.J., Valdivielso, A.F., and Etxeberria, I., 2009, Design and test of a multitooth tool for CFRP milling, *Journal of Composite Materials*, 43(26), pp. 3275-3290.
- [11] Enemuoh, E.U., El-Gizawy, A.S., and Okafor, A.C., 2001, An approach for development of damage-free drilling of carbon fiber reinforced thermosets, *International Journal of Machine Tools and Manufacture*, 41(12), pp. 1795-1814.
- [12] Gaitonde, V.N., Karnik, S.R., Rubio, J.C., Correia, A.E., Abrao, A.M., and Davim, J.P., 2008, Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites, *Journal of Materials Processing Technology*, 203(1-3), pp. 431-438.
- [13] Gay, D., Hoa, S.V., and Tsai, S.W., 2003, *Composite Materials Design and Applications*, CRC Press, Boca Raton, FL, USA.
- [14] Guu, Y.H., Hocheng, H., Tai, N.H., and Liu, S.Y., 2001, Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, *Journal of Materials Science*, 36(8), pp. 2037-2043.
- [15] Hashmi, M.S.J., Yilbas B.S., and Naher, S., 2009, Milling of carbon fiber reinforced plastics, *Advanced Materials Research*, 83-86, pp. 49-55.
- [16] Hilsch R., 1947, The use of the expansion of gases in a centrifugal field as cooling process, *The Review of Scientific Instruments*, 18(2), pp. 108-1113.
- [17] Hocheng, H., and Tsao, C.C., 2003, Comprehensive analysis of delamination in drilling

- of composite materials with various drill bits, *Journal of Materials Processing Technology*, 140(1-3), pp. 335-339.
- [18] Hocheng, H., and Tsao, C.C., 2006, Effect of special drill bits on drilling-induced delamination of composite materials, *Journal of Machine Tools and Manufacture*, 46(12-13), pp. 1403-1416.
 - [19] Klock, F., and Eisenblatter, G., 1997, Dry cutting, *Annals of the CIRP*, 46(2), pp. 519-526.
 - [20] Lambert, B.K., 1987, Cutting and drilling of composite materials, *The Carbide and Tool Journal*, 19(5), pp. 31-34.
 - [21] Li, Z.C., Pei, Z.J., Sisco, T., Micale, A.C., and Treadwell, C., 2007, Experimental study on rotary ultrasonic machining of graphite/epoxy panel, *Proceedings of the ASPE 2007 Spring Topical Meeting on Vibration Assisted Machining Technology*, April 16-17, Chapel Hill, NC, USA, pp. 52-57.
 - [22] Liu, C.X., and Hu, R.S., 1997, Cooling air from vortex tube applied to tool cooling, *Manufacturing Technology and Machine Tool*, 1, pp. 30-31. (In Chinese).
 - [23] Liu, J., and Chou, Y. K., 2005, Vortex-tube cooling for tool wear reduction in A390 dry machining, *World Tribology Congress III*, September 12-16, Washington D.C., USA, pp. 837-838.
 - [24] Liu, J., and Chou, Y.K., 2007, On temperatures and tool wear in machining hypereutectic Al-Si alloys with vortex-tube cooling, *International Journal of Machine Tools and Manufacture*, 47(3-4), pp. 635-645.
 - [25] Mallick, P.K., 1997, *Composite Engineering Handbook*, Marcel Dekker Inc., New York, NY, USA.

- [26] Nguyen, T., and Zhang, L.C., 2003, An assessment of the applicability of cold air and oil mist in surface grinding, *Journal of Materials Processing Technology*, 140(1-3), pp. 224-230.
- [27] Park, K.Y., Choi, J.H., and Lee, D.G., 1995, Delamination-free and high efficiency drilling of carbon fiber reinforced plastics, *Journal of Composite Materials*, 29(15), pp. 1988-2002.
- [28] Ruegg, C.H., and Habermeier, J., 1981, Composite propeller shafts: design and optimization, *Automotive Engineer*, 6(3), pp. 13-15.
- [29] Rubio, J.C., Abrao, A.M., Faria, P.E., Correia, A.E., and Davim, J.P., 2008, Delamination in high speed drilling of carbon fiber reinforced plastic (CFRP), *Journal of Composite Materials*, 42(15), pp. 1523-1532.
- [30] Ramulu M., Branson T., and Kim D., 2001, A study on the drilling of composite and titanium stacks, *Composite Structure*, 54(1), pp. 67-77.
- [31] Sadat, A.B., 1995, Delamination and other types of damage of graphite/epoxy composite caused by machining, *American Society of Mechanical Engineers, Applied Mechanics Division*, 208, pp. 41-52.
- [32] Schwartz, M.M., 1992, *Composite Materials Handbook*, Second edition, McGraw-Hill, Columbus, OH, USA.
- [33] Sreejith, P.S., and Ngoi, B.K.A., 2000, Dry machining: machining of the future, *Journal of Materials Processing Technology*, 101(1-3), pp. 287-291.
- [34] Tsao, C.C., and Hocheng, H., 2004, Taguchi analysis of delamination associated with various drill bits in drilling of composite material, *International Journal of Machine Tools and Manufacture*, 44(10), pp. 1085-1090.

- [35] Tsao, C.C., and Hocheng, H., 2005, Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials, *International Journal of Machine Tools and Manufacture*, 45(2), pp. 125-130.
- [36] Tsao, C.C., and Hocheng, H., 2007, Effect of tool wear on delamination in drilling composite materials, *International Journal of Mechanical Sciences*, 49(8), pp. 983-988.

Chapter 14 - CFRP - Feasible Regions in Dry Drilling

Paper title:

Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions

Published in:

Journal of Reinforced Plastics and Composites (2012), Vol. 30, No. 10, pp. 899-906.

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Deines, T.W.¹, and Treadwell, C.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
2. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Carbon fiber reinforced plastic (CFRP) composites are attractive for a variety of applications due to their superior properties. Drilling is involved in many CFRP applications. Experiments have been successfully conducted to use rotary ultrasonic machining (RUM) for CFRP drilling. These experiments were conducted using either cutting fluids or cold air as coolant. RUM of CFRP composites without cutting fluids can eliminate problems caused by cutting fluids, such as high cost of cutting fluids and their disposal, pollution to the environment, and harm to human health. However, dry machining (machining without cutting fluids) also has its limitations, such as burning of machined surface, more friction and adhesion between tool and workpiece, and reduction in tool life. This paper presents an experimental study on feasible regions in rotary ultrasonic machining of CFRP using cold air as coolant. Three criteria (burning of machined surface, delamination, and tool blockage) were used to determine feasible regions. Each of four input variables (feedrate, tool rotation speed, ultrasonic power, and cold air pressure) was changed over a wide range so that its feasible region could be found.

Keywords: Carbon fiber reinforced plastic composite, Cold air, Drilling, Feasible region, Rotary ultrasonic machining, Vortex tube.

14.1 Introduction

Carbon fiber reinforced plastic (CFRP) composites have strong carbon fibers surrounded by a weaker plastic matrix. The fibers are to support the load. The matrix serves to distribute, hold, and protect the fibers and also to transmit the load to the fibers [Gay et al., 2003; Tong et al., 2002; Chung 2010].

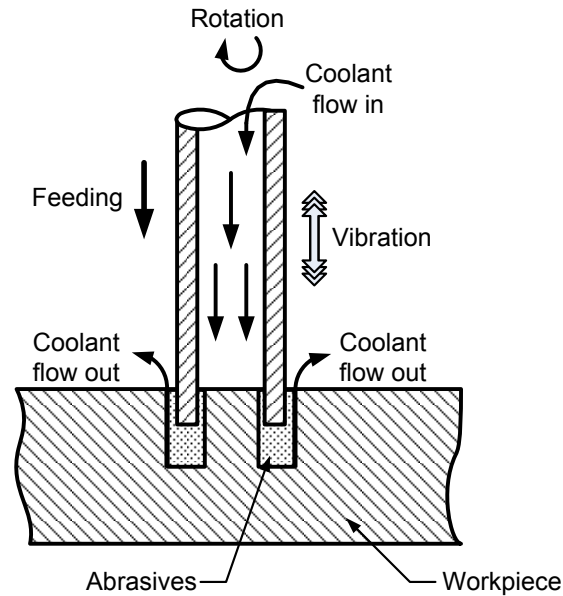
Superior prosperities of CFRP composites include low density (lower than aluminum), high strength (as strong as high-strength steels), high stiffness (stiffer than titanium), good

fatigue resistance, good creep resistance, low friction coefficient, good wear resistance, good toughness and damage tolerance, corrosion resistance, good dimensional stability (about zero coefficient of thermal expansion), and high vibration damping ability [Arul et al., 2006; Sadat, 1995; Davim and Reis, 2003; Lambert, 1987; Sadat, 1995; Guu et al., 2001; Chung, 2010; Mallick, 1997; Schwartz, 1992; Morgan, 2005].

Due to their superior properties, CFRP composites are attractive for a variety of applications. They are used in many types of structures including aircraft, spacecraft, automobile, ship, bridge, athletic equipment, and leisure goods. They are employed in engine blades, power transmission shafts, machine spindles, robot arms, pressure vessels, and chemical containers [Park et al., 1995; Ruegg and Habermeier, 1981; Gay et al., 2003; Guu et al., 2001; Arul et al., 2006; Sadat, 1995].

Drilling is involved in many CFRP applications. Rotary ultrasonic machining (RUM) has been successfully used in CFRP drilling with and without cutting fluids as coolant [Li et al., 2007; Cong et al., 2011a]. It is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. Figure 14.1 illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrates axially at an ultrasonic frequency (for example, 20 kHz) and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf and keeps cutting temperature low.

Figure 14.1 Illustration of rotary ultrasonic machining.



Because cutting fluids have several detrimental effects, dry machining (machining without direct contact between cutting fluids and the tool-workpiece interface) is preferred when possible. The advantages of dry machining include less or no pollution to the environment as well as reduced cost in disposal of chips and cutting fluids. Deployment of cutting fluids counts for about 7-17% of the total cost of machining, while cutting tools count for only approximately 2-4% [Klock and Eisenblatter, 1997]. It is estimated that over 380 million liters of cutting fluids are used annually in the US and 1.2 million US workers are exposed to cutting fluids each year [Byers, 1994]. Some cutting fluids might be harmful to human health [Sreejith and Ngoi, 2000].

However, dry machining can potentially cause burning of machined surface, more friction and adhesion between tool and workpiece, reduction in tool life, noise of compressed air flow, ribbon-like chips which can lead to tool jam and high surface roughness [Liu and Hu, 1997; Sreejith and Ngoi, 2000; Nguyen and Zhang, 2003].

Experiments have been conducted to use cold air (instead of cutting fluids) as coolant in RUM of CRFP. Effects of input variables (ultrasonic power, tool rotation speed, and feedrate) on

cutting force, torque, surface roughness, and machined surface burning were studied [Cong et al., 2011a]. However, some values of these input variables were not feasible for practical use because they resulted in burning of machined surface, or workpiece delamination, or tool (core drill) blockage. It is desirable to know what values of each input variable are feasible. In the current literature, there are no reports on feasible regions of these input variables.

This paper reports an experimental study on feasible regions for RUM of CFRP using cold air as coolant. Three criteria (burning of machined surface, delamination, and tool blockage) were used to determine the feasible regions for each of the input variables (feedrate, tool rotation speed, ultrasonic power, and cold air pressure). There are four sections in this paper. Following this introduction section, Section 14.2 describes experimental conditions, workpiece material properties, and measurement procedures. Section 14.3 presents and discusses experimental results. Finally, conclusions are summarized in Section 14.4.

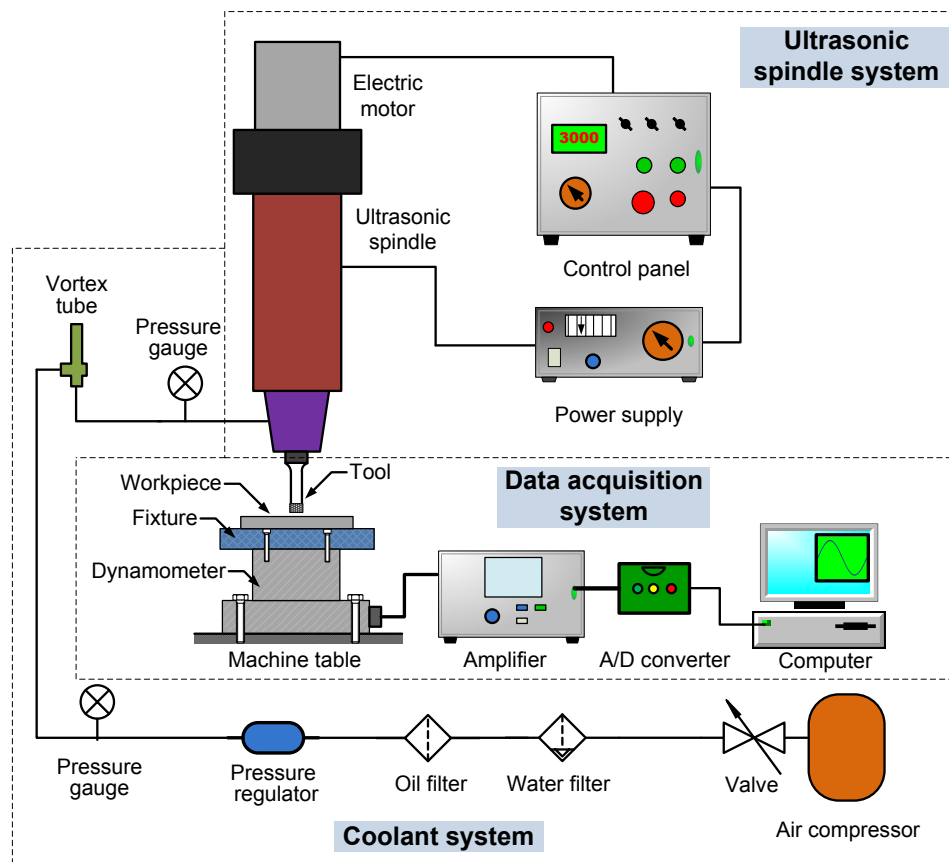
14.2 Experimental conditions and evaluation criteria

14.2.1 Experimental set-up

Drilling experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 14.2. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a cooling system. The ultrasonic spindle system was mainly comprised of an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converted (60 Hz) electrical supply to high-frequency (20 kHz) AC output. This high frequency electrical energy was provided to a piezoelectric converter (located inside the ultrasonic spindle) that converted electrical energy into mechanical vibration. The ultrasonic vibration from the converter was amplified and

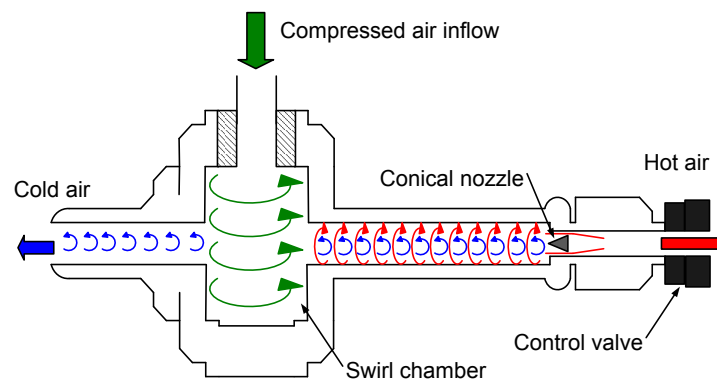
transmitted to the rotary tool. This caused the diamond tool attached to the spindle to vibrate in the direction perpendicular to the tool end face at 20 thousand times per second. The amplitude of ultrasonic vibration was adjusted by changing the setting of output control of the power supply. The motor attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds were obtained by adjusting the motor speed controller. The cooling system mainly included a vortex tube, air compressor, pressure regulator and valve, and pressure meters. It provided cold air to the spindle and the cutting interface.

Figure 14.2 Illustration of experimental set-up.



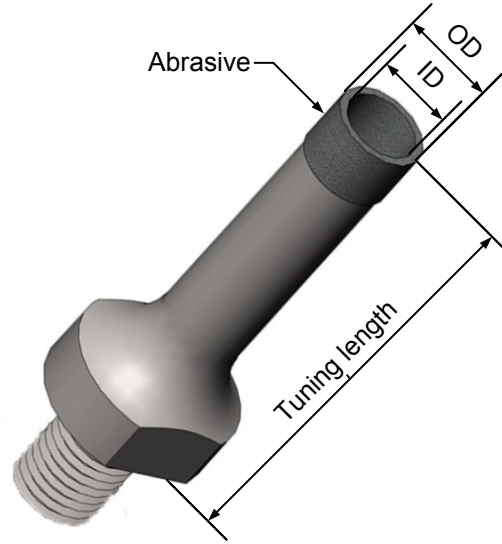
The cold air in this study was generated by a vortex tube (VT). As illustrated in Figure 14.3, VT is a simple mechanical device without any moving components. It separates a stream of compressed air into a hot and a cool branch [Ahlborn et al., 1994]. Compressed air is injected into a swirl chamber and accelerates to a high rotation rate. Due to the conical nozzle at the end of the tube, only the outer shell of the compressed air is allowed to escape at that end. The remainder of the air is forced to return in an inner vortex of a reduced diameter within the outer vortex. The hot air comes out of one end of the tube and cold air out of the other. A small control valve at the hot end, adjustable with the control valve, is used to control the air volume and temperature released from the cold end [Liu and Chou, 2005 & 2007; AiRTX 2010; Hilsch, 1947; Cong et al., 2008].

Figure 14.3 Illustration of vortex tube (after [AiRTX, 2008; Hilsch, 1947; Cong et al., 2008]).



Metal-bonded diamond core drills (NBR Diamond tool corp., LaGrangeville, NY, USA), as illustrated in Figure 14.4, were used. The outer and inner diameters (OD and ID) of the drills were 9.54 mm and 7.82 mm, respectively, and the tuning length was 45 mm. The diamond abrasives had mesh size of 60/80 and concentration of 100. The metal bond was of B type.

Figure 14.4 Illustration of a metal-bonded diamond core drill.



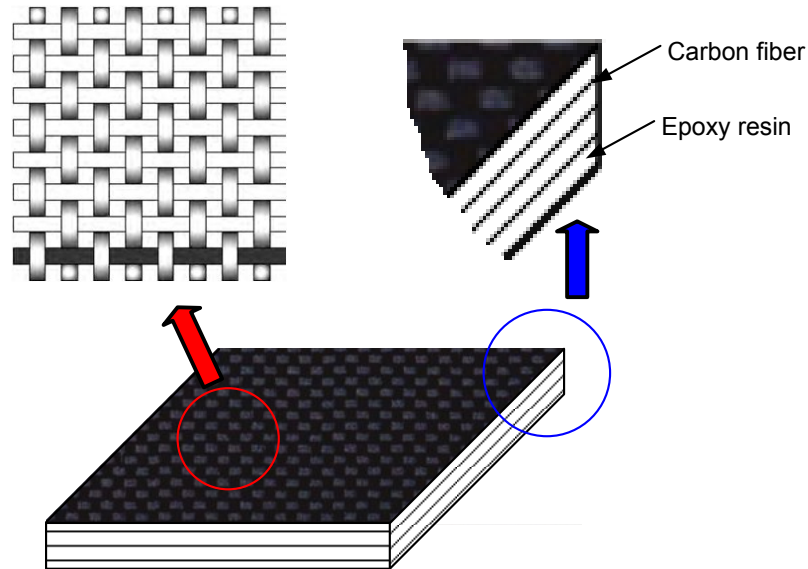
14.2.2 Workpiece size and material properties

The size of workpiece was 200 mm × 150 mm × 16 mm. The workpiece material was carbon fiber reinforced plastic (CFRP) composite, as illustrated in Figure 14.5. It was composed of carbon fibers and epoxy resin. Plain woven fabric of carbon fibers with an orientation of 0/90 degrees was used. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The workpiece contained 42 layers of carbon fibers. Workpiece material properties are listed in Table 14.1.

Table 14.1 Workpiece material properties.

Property	Unit	Value
Density	kg/m ³	1550
Hardness (Rockwell)	HRB	70-75
Elastic modulus of epoxy matrix	GPa	2.06 - 2.15
Tensile strength of epoxy matrix	MPa	80 - 85
Elastic modulus of carbon fiber	GPa	75 - 80
Tensile strength of carbon fiber	MPa	400 - 450

Figure 14.5 Illustration of CFRP.



14.2.3 Experimental conditions

On the basis of the experience from preliminary experiments and due to the limitations of the experimental set-up (for example, vibration frequency was fixed at 20 kHz on the machine), the experiments were focused on the study of the following input variables:

- Tool rotation speed: Rotational speed of tool;
- Feedrate: Feedrate of tool;
- Ultrasonic power: Percentage of power from ultrasonic power supply, which controls the ultrasonic vibration amplitude;
- Cold air pressure: Pressure of cold air at cold outlet of VT.

These input variables and their values are shown in Table 14.2. Four holes were drilled under each machining condition. Only two levels of cold air pressure, 40 psi and 50 psi, were used in the experiments, because the cooling system could not endure any air pressure higher than 50 psi. Furthermore, when cold air pressure was lower than 40 psi, feasible regions became very small.

Table 14.2 Input variables and their values.

Variable	Value
Ultrasonic power (%)	0; 20; 40; 60; 80
Tool rotation speed (rpm)	500; 1000; 2000; 3000; 4000; 5000; 6000
Feedrate (mm/s)	0.05; 0.1; 0.3; 0.5; 0.7; 0.9
Cold air pressure (psi)	40; 50
Cold air flow rate (lpm)	1.5

14.2.4 Criteria of feasible regions

Feasible regions were determined by three criteria:

- **Burning** sometimes happened on machined hole surfaces. During machining, the epoxy resin could be burned if cutting temperature was higher than a certain value. Burning of machined surface could result in many problems, such as higher surface roughness, lower hole accuracy, and lower strength [Rawat and Attia, 2009; Liu and Hu, 1997; Sreejith and Ngoi, 2000; Nguyen and Zhang, 2003].
- **Delamination** was caused by splitting or separating of a laminate into layers. It was one of the principle damages often observed when drilling of laminate composite materials. Figure 14.6 illustrates delamination damage (peel-up and push-down delamination) in composite material at the entrance and exit of the hole drilled by RUM. Delamination damage could result in lower hole accuracy, reduced tolerance, and lower strength [Campos Rubio et al, 2008ab; Jain and Yang, 1994; Stone and Krishnamurthy, 1996; Gaitonde et al., 2007; Paulo Davim et al., 2003 & 2007].
- **Tool blockage** would happen if the machined rod was stuck inside the core of the drill during RUM drilling process. Figure 14.7 shows tool blockage during RUM of CFRP. Tool blockage could lead to tool breakage.

Figure 14.6 Illustration of delamination.

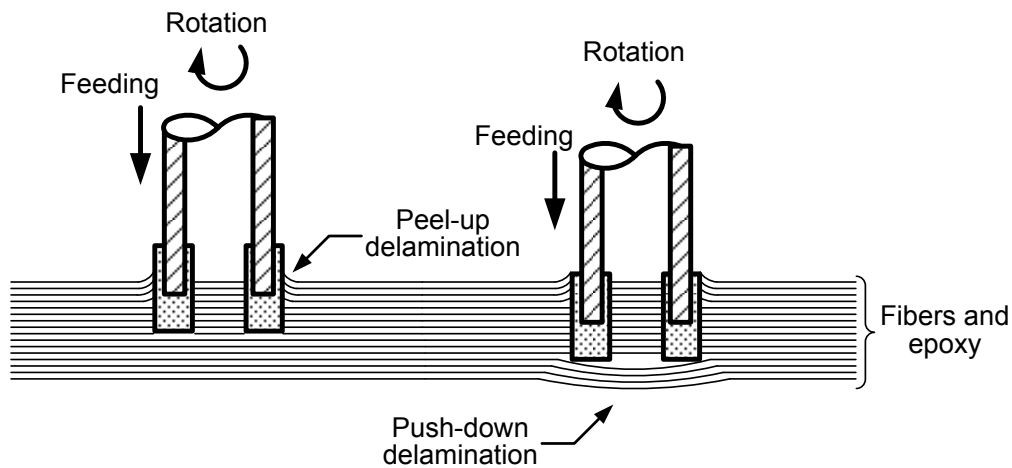
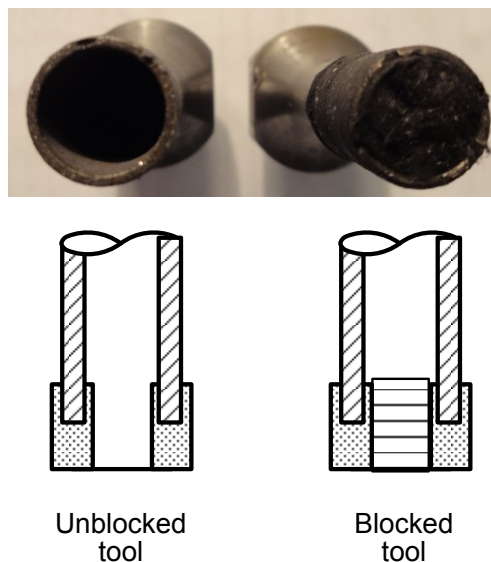


Figure 14.7 Illustration of tool blockage.



Each of the input variables in Table 14.2 was tested over a wide range. If one of these three criteria (burning of machined surface, workpiece delamination, and tool blockage) occurred under a value of an input variable, this value was marked as outside the feasible regions.

14.3 Experimental results

14.3.1 Feasible regions of tool rotation speed and feedrate

Figure 14.8 shows the feasible regions of tool rotation speed and feedrate. The range of tool rotation speed was from 500 to 6000 rpm and the range of feedrate was from 0.1 to 0.9 mm/s. The ultrasonic power was set at 40%.

Figure 14.8 Feasible regions of tool rotation speed and feedrate.

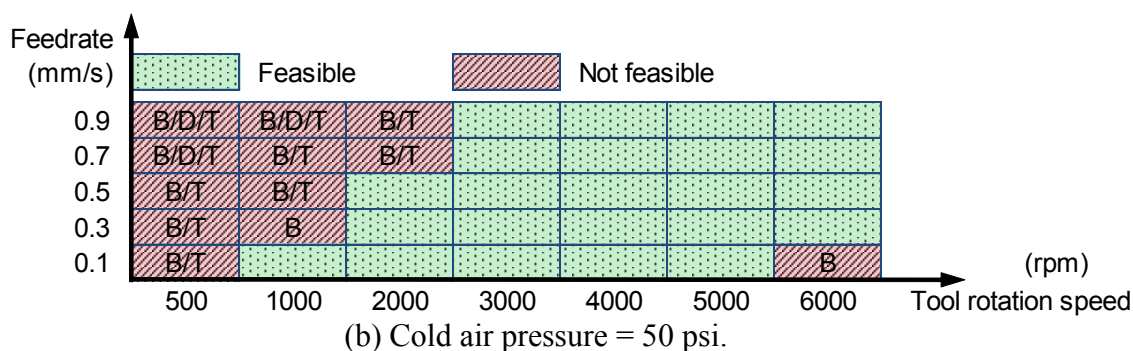
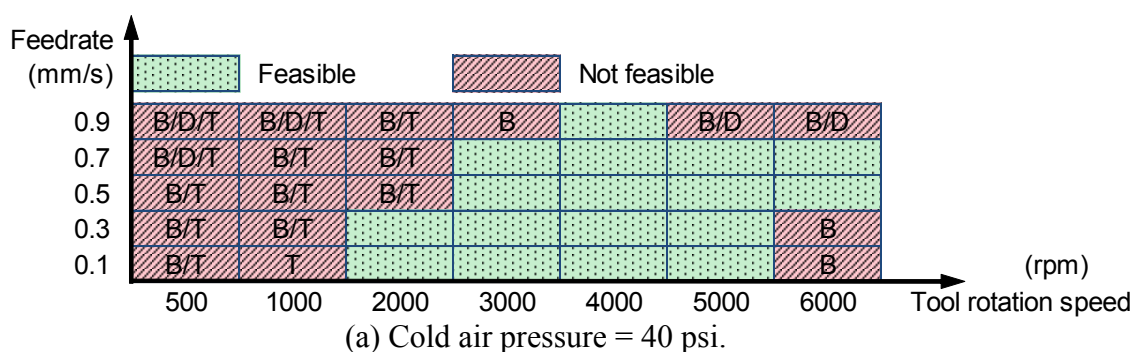


Figure 14.8(a) shows the feasible region with cold air pressure of 40 psi. When tool rotation speed was 1000 rpm or lower, dry machining was not feasible at any level of feedrate. Tool blockage (indicated by letter “T” in Figure 14.8) happened under all of these conditions. Burning (indicated by letter “B” in Figure 14.8) could be observed on most of machined holes.

Holes drilled with higher feedrate always had delamination (indicated by letter “D” in Figure 14.8). When tool rotation speed was 4000 rpm, dry machining was feasible at all levels of feedrate. At other levels of tool rotation speed (instead of 500, 1000, and 4000 rpm), dry machining was feasible at some levels of feedrate. For example, dry machining was feasible when tool rotation speed was 3000 or 5000 rpm and feedrate was from 0.1 to 0.7 mm/s, when tool rotation speed was 2000 rpm and feedrate was 0.1 or 0.3 mm/s, as well as when tool rotation speed was 6000 rpm and feedrate was 0.5 or 0.7 mm/s. Burning was the primary limiting criterion under these conditions, although workpiece delamination and tool blockage also occurred under some conditions.

Figure 14.8(b) shows the feasible region with cold air pressure of 50 psi. The feasible region was larger than that with cold air pressure of 40 psi. When tool rotation speed was from 3000 to 5000 rpm, dry machining was feasible at all levels of feedrate. However, when tool rotation speed was 1000 rpm or lower, dry machining was not feasible when feedrate = 0.1 mm/s and tool rotation speed = 1000 rpm). When tool rotation speed was 2000 rpm, dry machining was feasible only when feedrate was from 0.1 to 0.5 mm/s. When tool rotation speed was 6000 rpm, dry machining was feasible at all levels of feedrate except 0.1 mm/s.

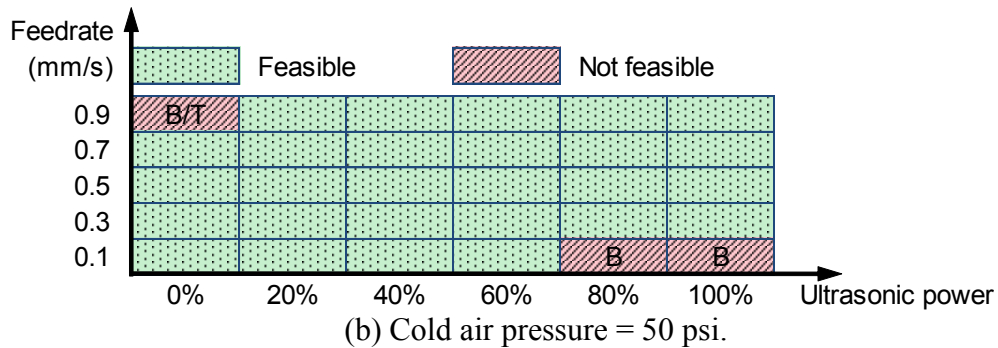
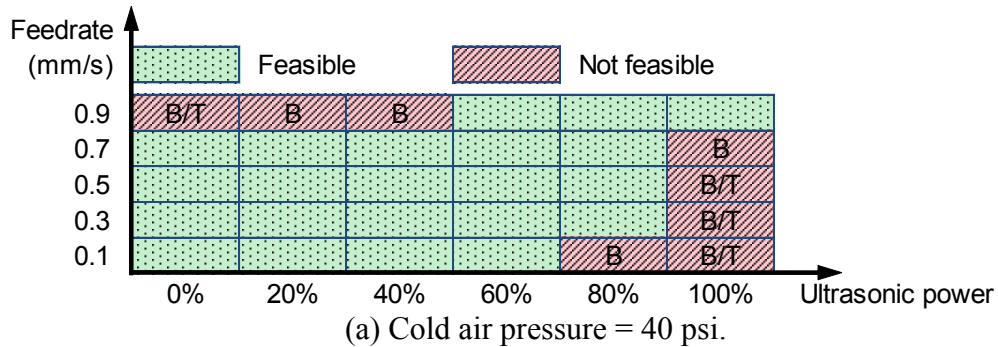
14.3.2 Feasible regions of ultrasonic power and feedrate

Figure 14.9 shows feasible regions of ultrasonic power and feedrate. Ultrasonic power was changed from 0 to 100% with an interval of 20%, feedrate was changed from 0.1 to 0.9 mm/s with an interval of 0.2 mm/s, and tool rotation speed was set at 3000 rpm.

With cold air pressure of 40 psi, dry machining was feasible when ultrasonic power $\leq 60\%$ and feedrate ≤ 0.7 mm/s. A combination of high feedrate (0.9 mm/s) and low ultrasonic power ($\leq 40\%$) or a combination of low feedrate and high ultrasonic power would cause burning of

machined surface or tool blockage. The feasible region became large when cold air pressure was increased from 40 to 50 psi.

Figure 14.9 Feasible regions of ultrasonic power and feedrate.



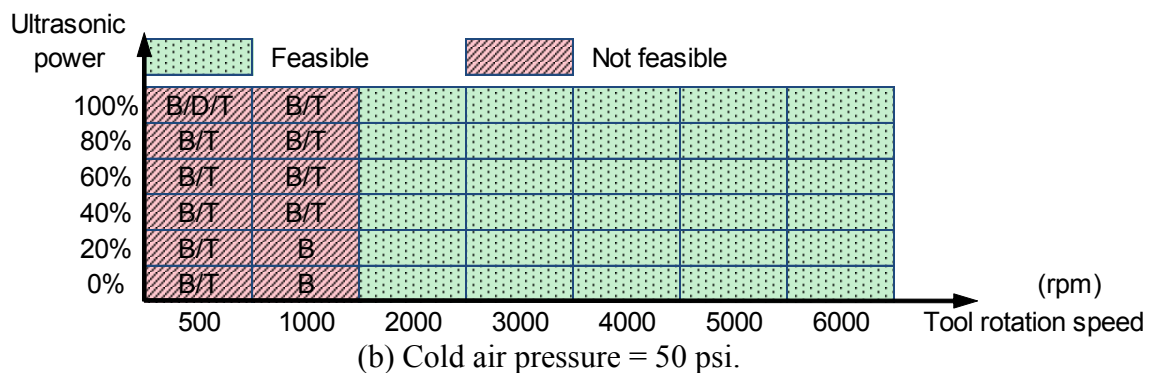
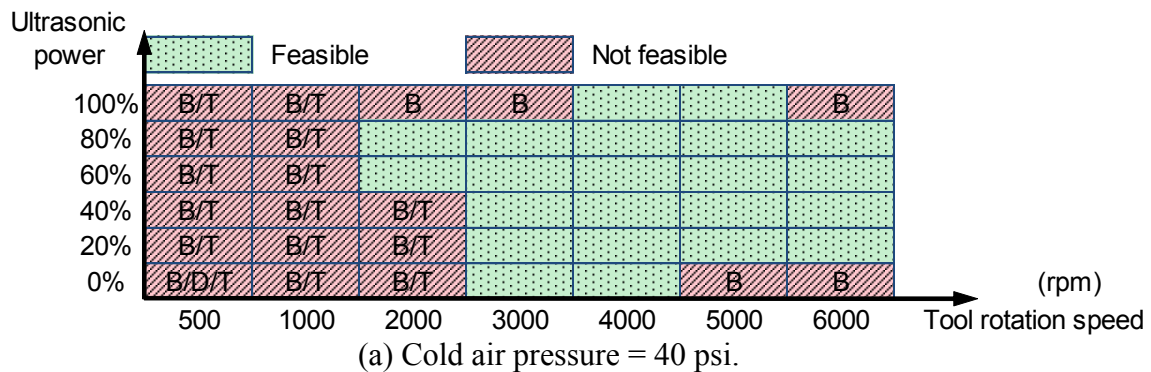
14.3.3 Feasible regions of tool rotation speed and ultrasonic power

Figure 14.10 shows feasible regions of tool rotation speed and ultrasonic power. The range of tool rotation speed was from 500 to 6000 rpm with an interval of 1000 (except 500 from 500 to 1000), the range of ultrasonic power was from 0% to 100% with an interval of 20%, and feedrate was fixed at 0.5 mm/s.

When tool rotation speed was ≥ 3000 rpm, dry machining was feasible under most conditions except when ultrasonic power = 100% and tool rotation speed = 3000 or 6000 rpm

and when ultrasonic power = 0 and tool rotation speed ≥ 5000 rpm (these combinations would result in burning of machined workpiece). When tool rotation speed was ≤ 2000 rpm, dry machining was only feasible when tool rotation speed = 2000 rpm and ultrasonic power = 60% or 80%. Other conditions would cause burning of machined surface, or burning and tool blockage, or burning and tool blockage and workpiece delamination. The feasible region became large when cold air pressure was increased from 40 to 50 psi. With cold air pressure of 50 psi, dry machining was feasible when tool rotation speed ≥ 2000 rpm (at all levels of ultrasonic power).

Figure 14.10 Feasible regions of tool rotation speed and ultrasonic power.



14.4 Conclusions

This paper reports an experimental study on rotary ultrasonic machining of CFRP using cold air as coolant. The aim of this study is to determine the feasible regions of input variables. The following conclusions are drawn from this study:

- (a) Higher cold air pressure led to larger feasible regions.
- (b) Dry machining was not feasible when tool rotation speed was too low (≤ 2000 rpm) regardless of what levels of feedrate and ultrasonic power.
- (c) Dry machining was not feasible when high ultrasonic power ($\geq 80\%$) combined with low feedrate (≤ 0.7 mm/s).

The work report in this paper was experimental. In the future, fundamental research will be conducted to understand the mechanisms of these experimental results. For example, hypotheses will be proposed to explain why higher air pressure led to larger feasible regions. One hypothesis would be that higher air pressure reduces cutting temperature and lower temperature allows feasible regions to become larger. In order to test this hypothesis, cutting temperature will be measured with different levels of air pressure. Cutting temperature in rotary ultrasonic machining of titanium has been measured [Cong et al., 2011b] and the same measurement method can be used for the proposed fundamental research.

Acknowledgements

The work was supported by the National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to Mr. Bruno Renzi at N.B.R. Diamond tool Corp. for supplying the diamond core drills.

References

- [1] Ahlborn, B., Keller, J.U., Staudt, R., Treitz, G., and Rebhan, E., 1994, Limits of temperature separation in a vortex tube, *Journal of Physics D: Applied Physics*, 27(3), pp. 480-488.
- [2] AiRTX, 2010, How vortex tubes work, AiRTX Company Web site, <http://www.airtxinternational.com/vortex-tubes/>.
- [3] Arul, S., Vijayaraghavan, L., Malhotra, S.K., and Krishnamurthy, R., 2006, The effect of vibratory drilling on hole quality in polymeric composites, *International Journal of Machine Tools and Manufacture*, 46(3-4), pp. 252-259.
- [4] Byers, J.P., 2006, *Mentalworking Fluids*, Second edition, CRC press, Boca Raton, FL, USA.
- [5] Campos Rubio, J., Abrao, A.M., Faria, P.E., Esteves Correia, A., and Paulo Davim, J., 2008a, Effects of high speed in the drilling of glass fibre reinforced plastic: Evaluation of the delamination factor, *International Journal of Machine Tools and Manufacture*, 48(6), pp. 715-720.
- [6] Campos Rubio, J., Abrao, A.M., Faria, P.E., Esteves Correia, A., and Paulo Davim, J., 2008b, Delamination in high speed drilling of carbon fiber reinforced plastic (CFRP), *Journal of Composite Materials*, 42(15), pp. 1523-1532
- [7] Chung, D.D.L., 2010, *Composite Materials Science and Applications*, Second edition, Springer-Verlag London Limited., London, UK.
- [8] Cong, W.L., and Pei, Z.J., 2008, Dry machining using vortex-tube generated cold air as coolant: A literature review, *Proceedings of the ASME International Manufacturing Science and Engineering Conference*, Evanston, IL, United states, October 7-10.

- [9] Cong, W.L., Feng, Q., Deines, T., Pei, Z.J., and Treadwell, C., 2011a, Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables, Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference, Corvallis, OR, USA, June 13-17.
- [10] Cong, W.L., Feng, Q., Deines, T., Pei, Z.J., and Treadwell, C., 2011b, Experimental study on cutting temperature in rotary ultrasonic machining, 39th Annual SME North American Manufacturing Research Conference, Corvallis, OR, USA, June 13-17.
- [11] Gaitonde, V.N., Karnik, S.R., Campos Rubio, J., Esteves Correia, A., Abrão, A.M., and Paulo Davim, J., 2007, Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites, Journal of Materials Processing Technology, 203(1-3), pp. 431-438.
- [12] Gay, D., Hoa, S.V., and Tsai, S.W., 2003, Composite Materials Design and Applications, CRC press, Boca Raton, FL, USA.
- [13] Guu, Y.H., Hocheng, H., Tai, N.H., and Liu, S.Y., 2001, Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, Journal of Materials Science, 36(8), pp. 2037-2043.
- [14] Jain, S., and Yang, D.C.H., 1994, Delamination-free drilling of composite laminates, Journal of Engineering for Industry, 116(4), pp. 475-481
- [15] Klock, F., and Eisenblatter, G., 1997, Dry cutting, Annals of the CIRP, 46(2), pp. 519-526.
- [16] Lambert, B.K., 1987, Cutting and drilling of composite materials, The Carbide and Tool Journal, 19(5), pp. 31-34.
- [17] Li, Z.C., Pei, Z.J., Sisco, T., Micale, A.C. and Treadwell, C., 2007, Experimental study on rotary ultrasonic machining of graphite/epoxy panel, Proceedings of the ASPE 2007 Spring

- Topical Meeting on Vibration Assisted Machining Technology, Chapel Hill, NC, USA, pp. 52-57, April 16-17.
- [18] Liu, C.X., and Hu, R.S., 1997, Cooling air from vortex tube applied to tool cooling, *Manufacturing Technology and Machine Tool*, Vol. 1, pp. 30-31. (In Chinese).
- [19] Liu, J., and Chou, Y.K., 2005, Vortex-tube cooling for tool wear reduction in A390 dry machining, *World Tribology Congress III*, Washington D.C., USA, pp. 837-838.
- [20] Liu, J., and Chou, Y.K., 2007, On temperatures and tool wear in machining hypereutectic Al-Si alloys with vortex-tube cooling, *International Journal of Machine Tools and Manufacture*, 47(3-4), pp. 635-645.
- [21] Mallick, P.K., 1997, *Composite Engineering Handbook*, Marcel Dekker Inc, New York, NY, USA.
- [22] Morgan, P., 2005, *Carbon Fibers and their composites*, CRC Press, Taylor & Francis Group, Boca Raton, FL, USA.
- [23] Nguyen, T., and Zhang, L.C., 2003, An assessment of the applicability of cold air and oil mist in surface grinding, *Journal of Materials Processing Technology*, 140(1-3), pp. 224-230.
- [24] Park, K.Y., Choi, J.H., and Lee, D.G., 1995, Delamination-free and high efficiency drilling of carbon fiber reinforced plastics, *Journal of Composite Materials*, 29(15), pp. 1988-2002.
- [25] Paulo Davim, J., and Reis, P., 2003, Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, *Materials and Design*, 24(5), pp. 315-324.
- [26] Paulo Davim, J., Campos Rubio, J., Abrao A.M., 2007, A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates, *Composites Science and Technology*, 67(9), pp. 1939-1945.

- [27] Rawat, S., and Attia, H, 2009, Characterization of the dry high speed drilling process of woven composites using machinability maps approach, CIRP Annals - Manufacturing Technology, 58(1), pp. 105-108.
- [28] Ruegg, C.H., and Habermeier, J., 1981, Composite propeller shafts: design and optimization, Automotive Engineer, 6(3), pp. 13-15.
- [29] Sadat, A.B., 1995, Delamination and other types of damage of graphite/epoxy composite caused by machining, American Society of Mechanical Engineers, Applied Mechanics Division, Vol. 208, pp. 41-52.
- [30] Schwartz, M.M., 1992, Composite Materials Handbook, Second edition, McGraw-Hill, Columbus, OH, USA.
- [31] Sreejith, P.S., and Ngoi, B.K.A., 2000, Dry Machining: Machining of the Future, Journal of Materials Processing Technology, 101(1-3), pp. 287-291.
- [32] Stone, R., and Krishnamurthy, K., 1996, A neural network thrust force controller to minimize delamination during drilling of graphite-epoxy laminates, International Journal of Machine Tools and Manufacture, 36(9), pp. 985-1003.
- [33] Tong, L., Mouritz A.P., and Bannister M.K., 2002, 3D Fibre Reinforced Polymer Composites, Elsevier Science Ltd, Oxford, UK.

Chapter 15 - CFRP - A Study on Power Consumption

Paper title:

Rotary ultrasonic machining of CFRP composites: a study on power consumption

Published in:

Ultrasonics (2012), Vol. 52, No. 8, pp. 1030-1037.

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Deines, T.W.¹, Srivastava A.², Riley L.³, and Treadwell, C.⁴

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
2. TechSolve Inc. Cincinnati, OH 45237, USA
3. Department of Electrical and Computer Engineering, Kansas State University, Manhattan, KS 66506, USA
4. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Carbon fiber reinforced plastic (CFRP) composites are very difficult to machine. A large number of holes need to be drilled in CFRP for many applications. Therefore, so it is important to develop cost-effective drilling processes. CFRP has been drilled by rotary ultrasonic machining (RUM) successfully. The literature has reports about the effects of input variables on output variables (including cutting force, torque, surface roughness, tool wear, and workpiece delamination) in RUM of CFRP. However, there are no reports on power consumption in RUM of CFRP. This paper reports the first study on power consumption in RUM of CFRP. It reports an experimental investigation on effects of input variables (ultrasonic power, tool rotation speed, feedrate, and type of CFRP) on power consumption of each component (including ultrasonic power supply, spindle motor, coolant pump, and air compressor) and the entire RUM system.

Keywords: Carbon fiber reinforced plastic composite, Drilling, Grinding, Power consumption, Rotary ultrasonic machining.

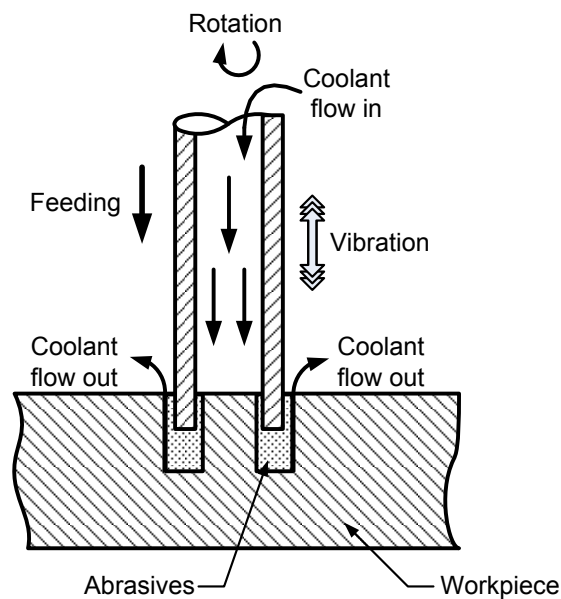
15.1 Introduction

Carbon fiber reinforced plastic (CFRP) composites are increasingly used as primary structural materials in the aerospace industry [Mangalgiri, 1999]. Superior properties of CFRP include low density (lower than aluminum); high strength (as strong as high-strength steels); high stiffness (stiffer than titanium); good toughness; good fatigue, creep, wear, and corrosion resistance; low friction coefficient; good dimensional stability (about zero coefficient of thermal expansion); and high vibration damping ability [Chung DDL 2010; Arul et al. 2006; Sadat et al. 1995; Davim and Reis 2003; Lambert 1987; Guu et al., 2001; Mallick 1997; Schwartz 1992; Morgan 2005; Park et al. 1995; Ruegg and Habermeier 1981]. Due to some of these superior properties, CFRPs are very difficult to machine. A large number of holes need to be drilled in

CFRP for many applications (especially in aircraft assembling) [Boeing Co. Web]. Therefore, it is important to develop cost-effective drilling processes.

CFRP has been drilled by rotary ultrasonic machining (RUM) successfully [Li et al. 2007; Cong et al. 2011abcd, Feng et al. 2011]. RUM is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. Figure 15.1 illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During machining, the rotating tool vibrates axially at an ultrasonic frequency (typically 20 kHz) and feeds along its axial direction towards the workpiece. Coolant is pumped through the core of the cutting tool, washing away the swarf and preventing the cutting zone from overheating.

Figure 15.1 Illustration of rotary ultrasonic machining.



The literature contains several studies on RUM of CFRP. Effects of input variables (including ultrasonic power, tool rotation speed, feedrate, and coolant type) on output variables (including cutting force, torque, surface roughness, delamination, and tool wear) have been

investigated [Li et al. 2007; Cong et al. 2011abcd, Feng et al. 2011]. Using the same CFRP workpiece material and similar machining conditions, twist drilling and RUM have been compared [Cong et al. 2011d]. Also, to reduce the costs associated with cutting fluids, RUM of CFRP using cold air as coolant has been studied [Cong et al. 2011abc]. Feasible regions in RUM of CFRP using cold air as coolant have been identified [Cong et al. 2011b]. A comparison of RUM of CFRP using cold air and cutting fluid has been made [Cong et al. 2011c]. These studies have shown that ultrasonic vibration in RUM can reduce cutting force, torque, cutting temperature, workpiece delamination, and tool wear.

The literature has no reports on power consumption in RUM. This study is the first to investigate power consumption in RUM of CFRP. It reports an experimental investigation on effects of input variables (including ultrasonic power, tool rotation speed, feedrate, and type of CFRP) on power consumption of each component (including ultrasonic power supply, spindle motor, coolant pump, and air compressor) and the entire RUM system. It also provides the percentage of each component's power consumption relative to the entire RUM system's power consumption under each experimental condition. There are four sections in this paper. Following this introduction section, Section 15.2 describes workpiece material properties, experimental conditions, and measurement procedures. Section 15.3 presents and discusses experimental results. Finally, conclusions are summarized in Section 15.4.

15.2 Experimental conditions

15.2.1 Workpiece material properties

CFRP composites were composed of carbon fibers and epoxy resin. Based on carbon fiber structures, CFRP composites used in this study can be classified into four types: wide yarn

woven, thin yarn woven, flake, and unidirectional continuous. Their material properties are listed in Table 15.1. The fiber structures are illustrated in Figure 15.2. Specifications of these structures are shown in

Table 15.2.

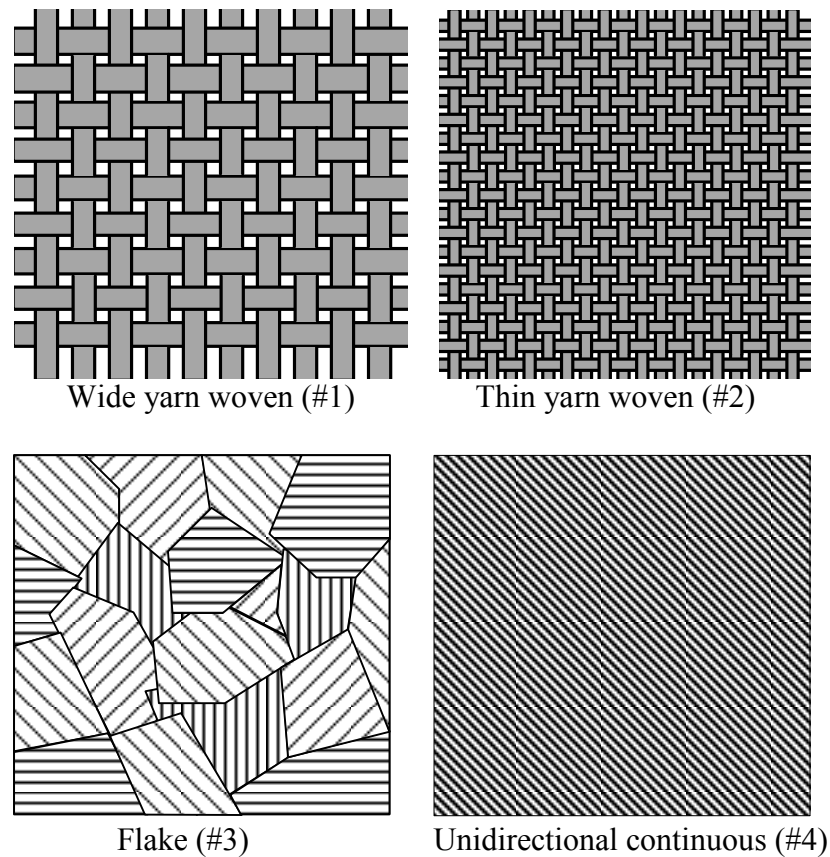
Table 15.1 Workpiece material properties.

Property	Unit	Value
Density of CFRP	kg/m ³	1550
Hardness (Rockwell)	HRB	70-75
Density of epoxy matrix	kg/m ³	1200
Elastic modulus of epoxy matrix	GPa	4.5
Tensile strength of epoxy matrix	MPa	130
Poisson's ratio of epoxy matrix	/	0.4
Density of carbon fiber	kg/m ³	1750
Elastic modulus of carbon fiber	GPa	230
Tensile strength of carbon fiber	GPa	5
Poisson's ratio of carbon fiber	/	0.3

Table 15.2 Specifications of carbon fiber structures of different CFRP types.

CFRP	Fiber structure	Orientation	Fiber size	Number of Layers	Thickness
#1	Wide yarn woven	0°/90°	2.5 mm by 0.2 mm fiber yarn	42	16 mm
#2	Thin yarn woven	0°/90°	0.35 mm by 0.1 mm fiber yarn	20	7 mm
#3	Flake	N/A	0.1 mm thickness fiber flake	N/A	12 mm
#4	Unidirectional continuous	45°	0.2 mm fiber layer	24	18 mm

Figure 15.2 Fiber structures of CFRP.

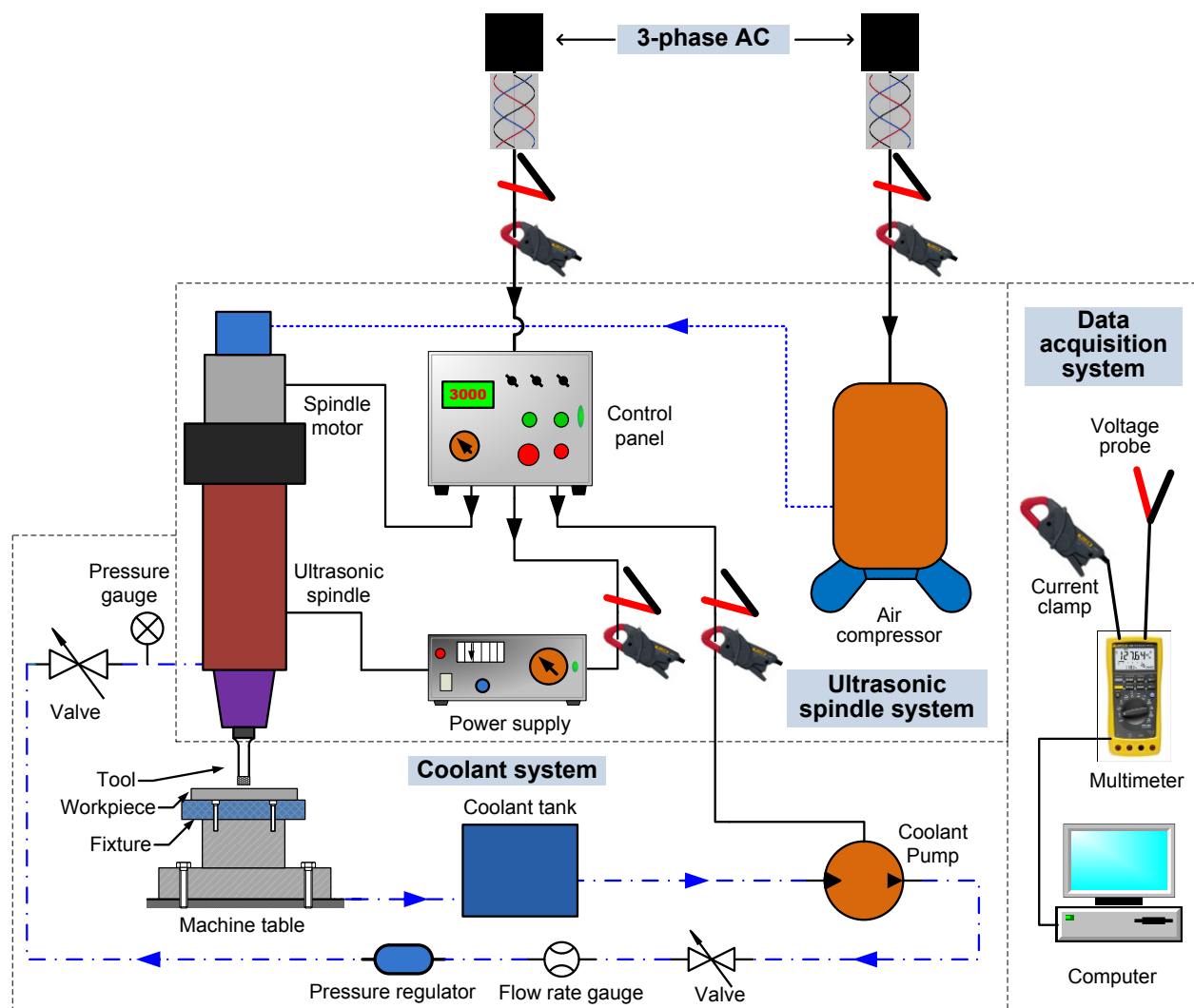


15.2.2 Experimental set-up

The experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 15.3. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a cooling system. The ultrasonic spindle system was comprised of an ultrasonic spindle, a power supply, and a spindle motor with speed controller. The power supply converted (60 Hz) electrical supply to high-frequency (20 kHz) electrical energy. This high-frequency electrical energy was provided to a piezoelectric converter (located in the ultrasonic spindle) that changed high-frequency electrical energy into mechanical vibration. The ultrasonic vibration was amplified and

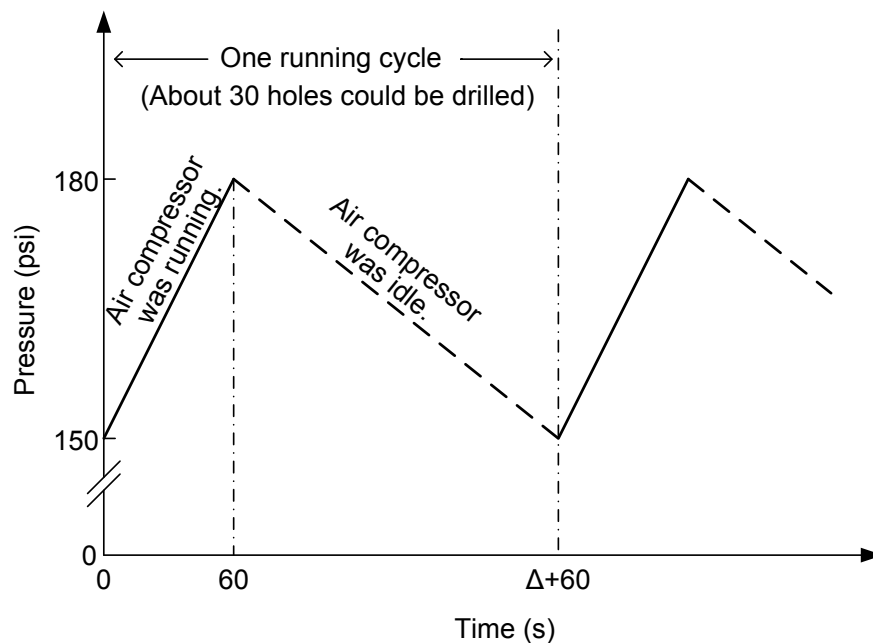
transmitted to the cutting tool. This caused the cutting tool to vibrate at the frequency of 20 kHz. The amplitude of ultrasonic vibration could be adjusted by changing the setting of output control of the power supply. A motor (SJ-PF, Mitsubishi Electric Corp., Tokyo, Japan) attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds were obtained by adjusting the speed controller. The cooling system was comprised of pump, coolant tank, pressure regulator, flow rate and pressure gauges, and valves. The cooling system provided coolant to the spindle and the interface of machining.

Figure 15.3 Illustration of experimental set-up.



The up and down movement of the spindle was driven (through a hydraulic cylinder) by high-pressure compressive air. The compressive air was provided by a stand-alone air compressor (CI523E80V, North Central Air, Downs, KS, USA). The air compressor started running if the air pressure was below 150 psi. The air compressor would keep running until the air pressure reached 180 psi. The air pressure decreased as each hole was drilled. About 30 holes could be drilled within one running cycle of the air compressor. This working cycle of the air compressor is illustrated in Figure 15.4.

Figure 15.4 Illustration of the working cycle of the air compressor.



Cutting tools used were metal-bonded diamond core drills (NBR Diamond Tool Corp., LaGrangeville, NY, USA), as illustrated in Figure 15.5. The outer and inner diameters (OD and ID) of the cutting tools were 9.54 mm and 7.82 mm, respectively, and tuning length was 45 mm.

The diamond abrasives had mesh size of 80/100 and concentration of 100. The metal bond was of B type.

Following input variables were varied in the experiments:

- Types of CFRP: Different CFRP fiber structures;
- Spindle speed: Rotational speed of cutting tool;
- Feedrate: Feedrate of cutting tool;
- Ultrasonic power: Percentage of power from ultrasonic power supply. As illustrated in

Figure 15.6, there was an almost linear relationship between ultrasonic power and ultrasonic vibration amplitude and higher ultrasonic power would produce higher ultrasonic vibration amplitude.

Figure 15.5 Illustration of a metal-bonded diamond core drill.

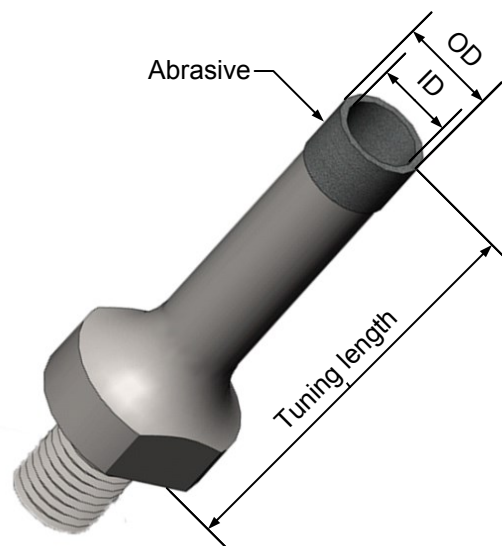
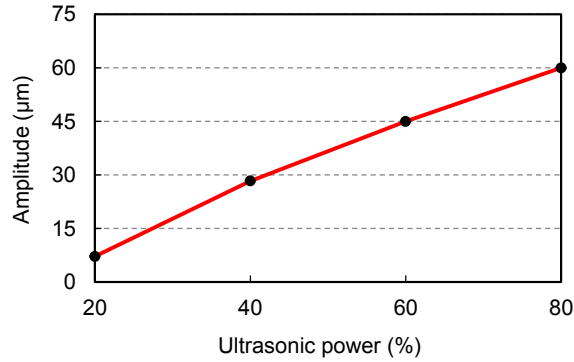


Table 15.3 Input variables and their values.

Variable	Value
Ultrasonic power (%)	0; 20; 40; 60; 80
Tool rotation speed (rpm)	1000; 2000; 3000; 4000; 5000

Feedrate (mm/s)	0.1; 0.3; 0.5; 0.7
CFRP type	Wide yarn woven; Thin yarn woven; Flake; Unidirectional continuous

Figure 15.6 Relationship between ultrasonic power and amplitude.



The values of these input variables are shown in Table 15.3. Only one variable was changed at a time while keeping other variables constant. The pressure and flow rate of coolant were kept the same at 40 psi and 1.5 lpm, respectively. Four holes were drilled under each machining condition.

15.2.3 Measurement procedures

The power consumption presented in this paper was the electricity energy (W) consumed when drilling a hole in the workpiece material divided by the workpiece thickness (mm). Note that the CFRP workpieces have different thicknesses.

Power consumption of the ultrasonic power supply was calculated by

$$W_u = \frac{U_u \cdot I_u}{3600 \cdot F} \quad (15.1)$$

where W_u was the power consumption of ultrasonic power supply (w·h/mm); U_u was the actual electricity voltage of ultrasonic power supply (V); I_u was the measured current of ultrasonic power supply during machining (A); and F was the feedrate (mm/s).

Power consumption of the coolant pump was calculated by

$$W_c = \frac{U_c \cdot I_c}{3600 \cdot F} \quad (15.2)$$

where W_c was the power consumption of coolant pump (w·h/mm); U_c was the voltage for coolant pump (V); I_c was the measured current of coolant pump during machining (A); and F was the feedrate (mm/s).

Power consumption of the air compressor was calculated by

$$W_a = \frac{U_a \cdot I_a \cdot t_a}{3600 \cdot n \cdot Th} \quad (15.3)$$

where W_a was the power consumption of air compressor (w·h/mm); U_a was the actual electricity voltage of air compressor (V); I_a was the measured current of air compressor when it was running (A); t_a was the period of time during which the air compressor was running (s); n was the number of holes that could be drilled within one air compressor activation cycle; and Th was the thickness of the workpiece (mm).

Because of the machine design, it is difficult to measure voltage and current of the spindle motor directly. Power consumption of the spindle motor was calculated by

$$W_s = W_p - W_u - W_c = \frac{U_p \cdot I_p}{3600 \cdot F} - W_u - W_c \quad (15.4)$$

where W_s was the power consumption of spindle motor (w·h/mm); W_p was power consumption of the control panel (w·h/mm); U_p was the measured electricity voltage of control panel (V); I_p was the measured current of the control panel during machining (A); and F was the feedrate (mm/s).

Power consumption of the entire RUM system was

$$W_{\text{RUM}} = W_a + W_p \quad (15.5)$$

The current and voltage of ultrasonic power supply, coolant pump, air compressor, and control panel (including spindle motor, ultrasonic power supply, and coolant pump) were measured by a data acquisition system. It consisted of a current clamp, a voltage probe, a multimeter (Model 189, Fluke Corp., Everett, WA), and a computer with Flukeview Forms software (Version 3.4, Fluke Corp., Everett, WA). The sampling rate was set at 1 Hz.

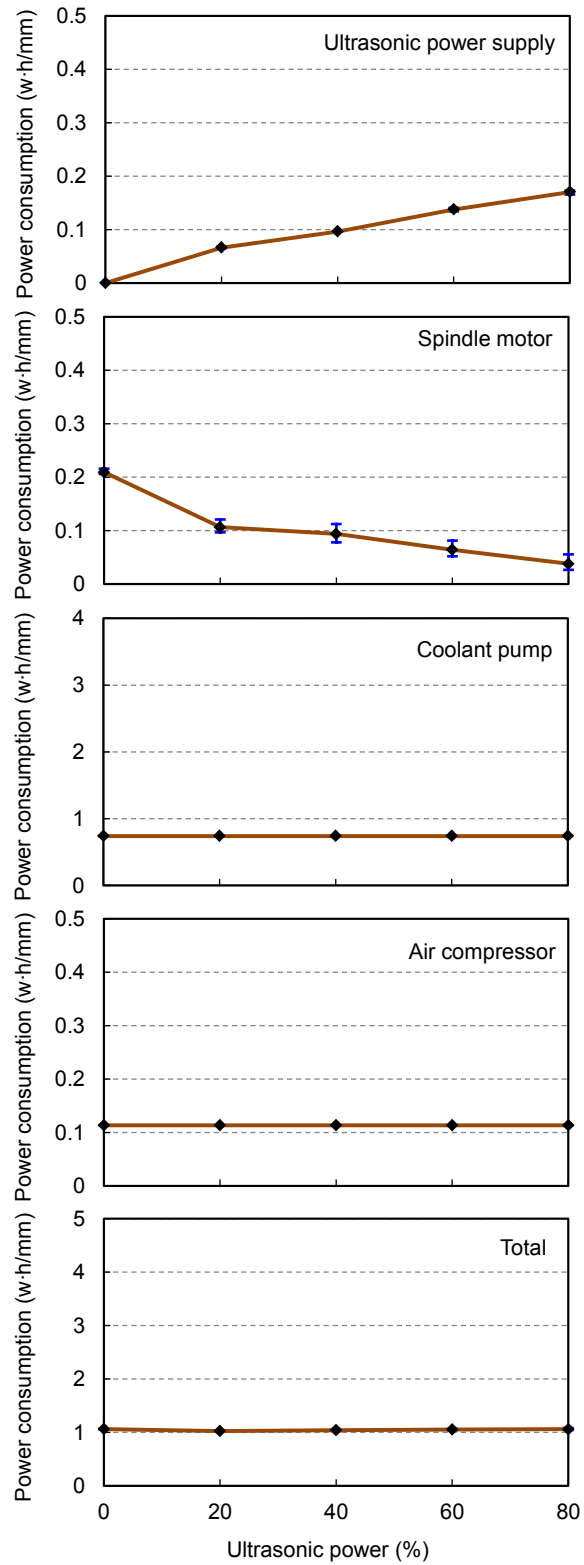
15.3 Results and discussion

15.3.1 Effects of ultrasonic power

Effects of ultrasonic power on power consumption for the entire RUM system and each component are shown in Figure 15.7. When ultrasonic power increased from 0 to 80%, power consumption of ultrasonic power supply increased slightly, power consumption of spindle motor decreased significantly, power consumption of coolant pump and air compressor kept constant, power consumption of the entire RUM system almost kept constant.

Power consumption percentages of each component under different settings of ultrasonic power are shown in Figure 15.8. For different settings of ultrasonic power, power consumption of coolant pump always had the highest percentage (about 70% of the entire RUM system power consumption), and power consumption percentage of air compressor kept unchanged at 11%. As the ultrasonic power increased, power consumption percentage of ultrasonic power supply increased from 0 to 16%, in contrast, spindle motor power consumption percentage decreased from 20% to 3%.

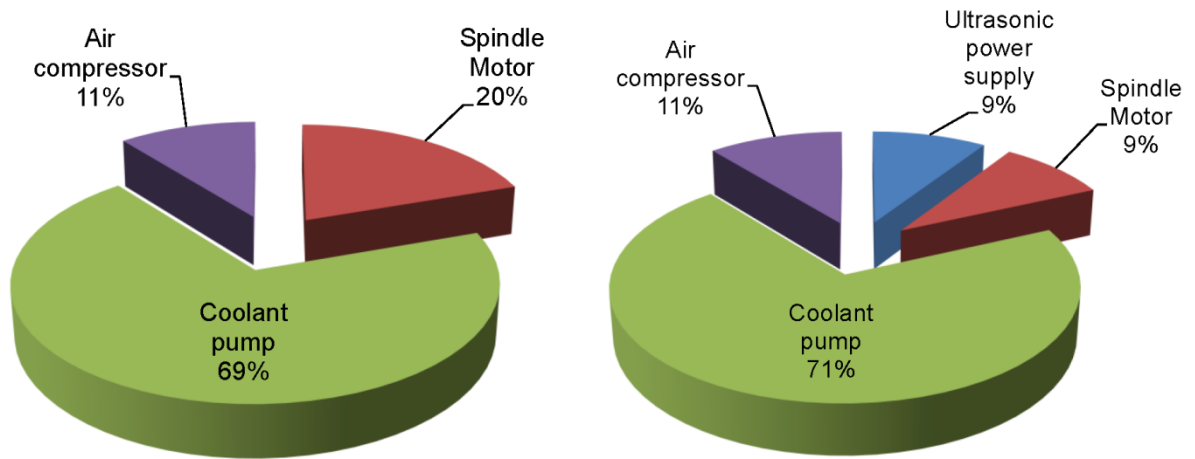
Figure 15.7 Effects of ultrasonic power.



(Tool rotation speed = 3000 rpm; Feedrate = 0.5 mm/s; CFRP #1)

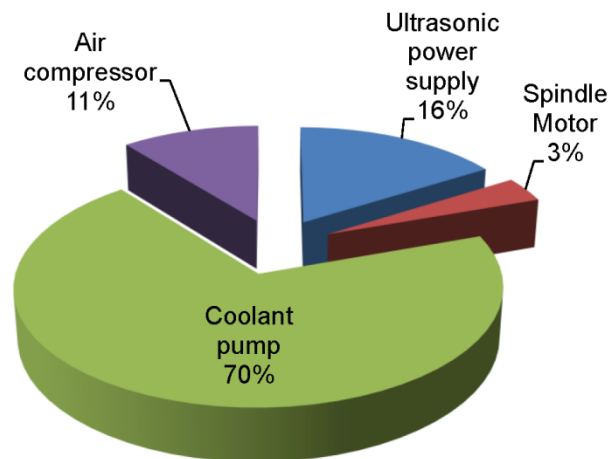
Effects of ultrasonic power on other output variables (including cutting force, torque, and surface roughness) had been studied [Cong et al., 2011c]. When ultrasonic power increased from 0% to 80%, cutting force and torque decreased. The decrease of cutting force and torque were about 20% and 40%, respectively. When ultrasonic power increased from 0 to 80%, surface roughness decreased first and then increased. Compared with RUM without ultrasonic power, the decrease of surface roughness was about 10%. It is noted that ultrasonic power in RUM can reduce cutting force, torque, and surface roughness, without increasing power consumption.

Figure 15.8 Power consumption percentage of each component under different settings of ultrasonic power.



(a) Ultrasonic power = 0%

(b) Ultrasonic power = 40%



(c) Ultrasonic power = 80%

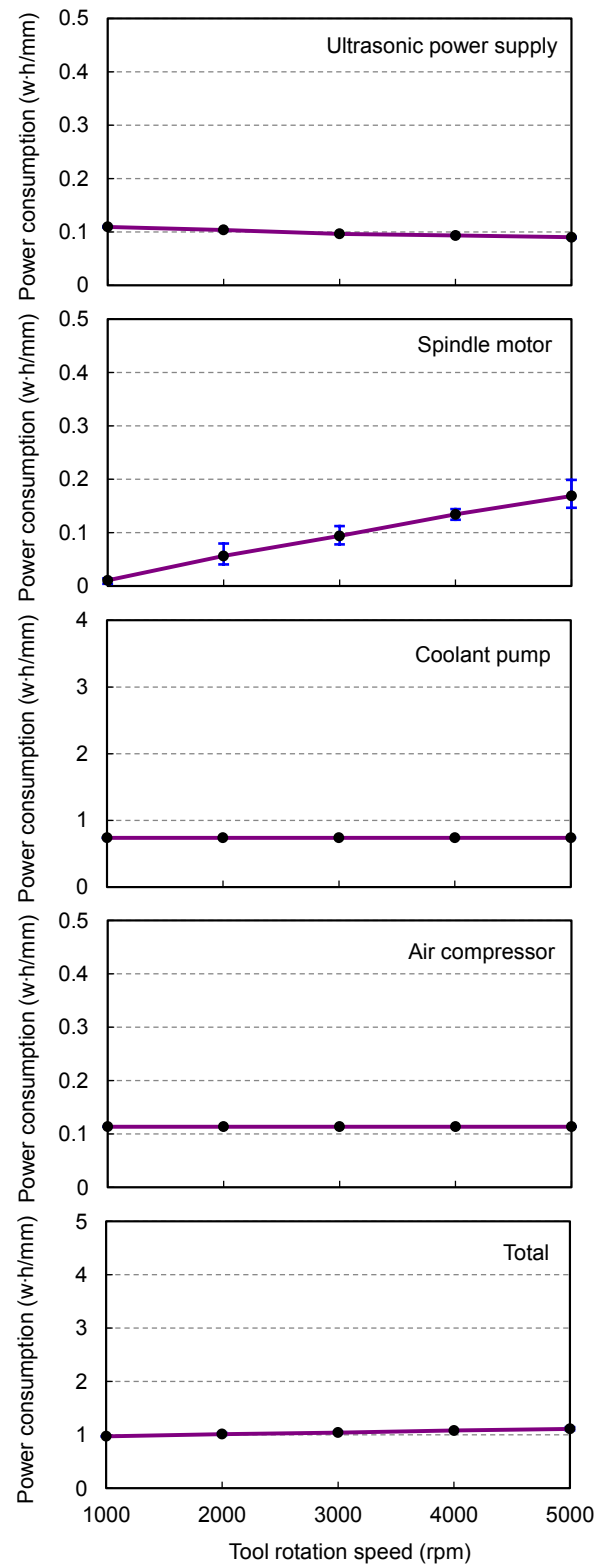
(Tool rotation speed = 3000 rpm; Feedrate = 0.5 mm/s; CFRP #1)

15.3.2 Effects of tool rotation speed

Effects of tool rotation speed on power consumption are shown in Figure 15.9. As tool rotation speed increased, power consumption of ultrasonic power supply decreased, power consumption of spindle motor increased dramatically, power consumption of coolant pump and air compressor kept unchanged, and power consumption of the entire RUM system increased slightly.

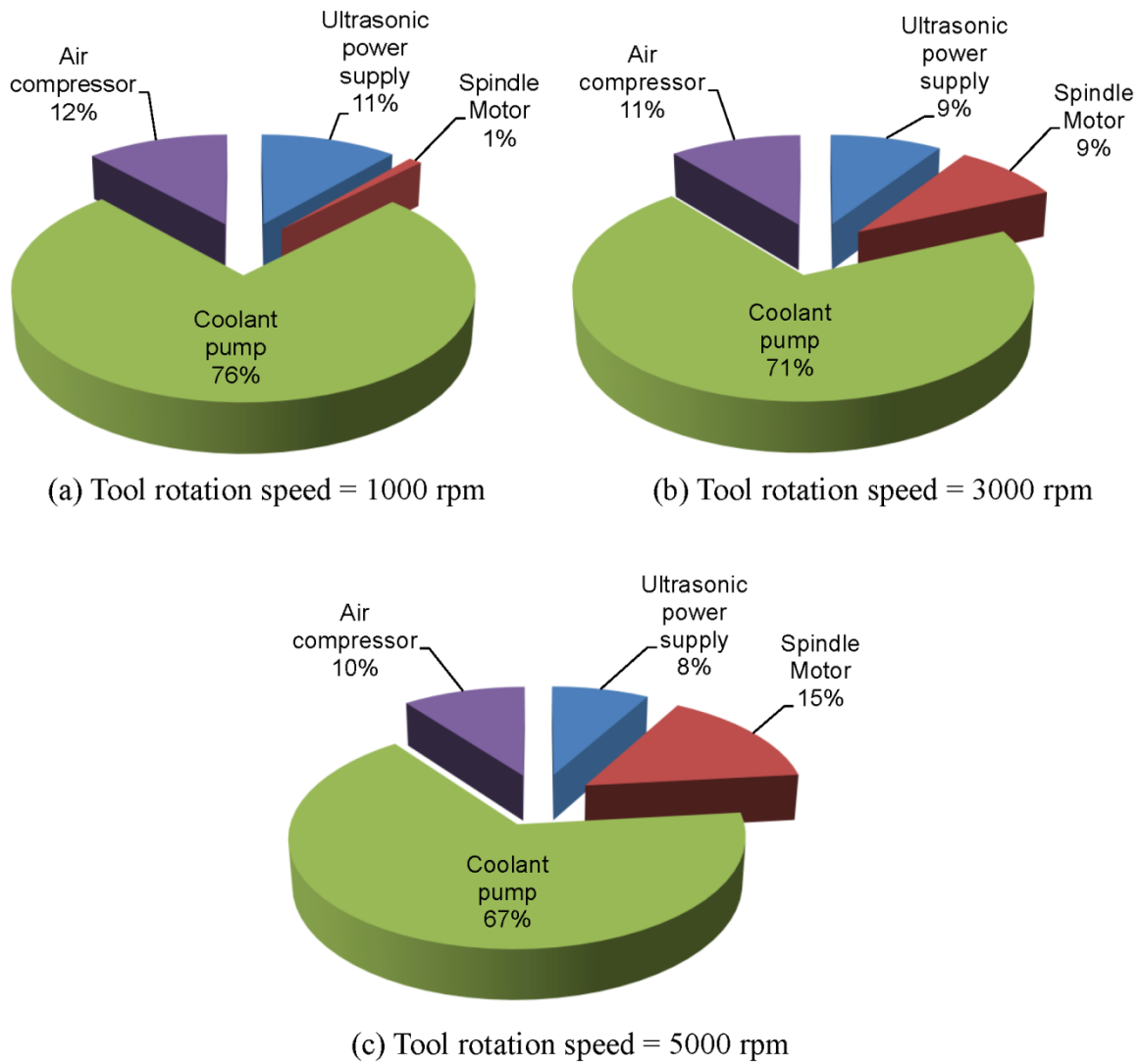
Power consumption percentages of each component under different settings of tool rotation speed are shown in Figure 15.10. For different settings of tool rotation speed, power consumption of coolant pump always had the largest percentage. As tool rotation speed increased from 1000 to 5000 rpm, power consumption percentage of ultrasonic power supply decreased slightly from 11% to 8%, power consumption percentage of spindle motor increased from 1% to 15%, power consumption percentage of coolant pump decreased from 76% to 67%, and power consumption percentage of air compressor decreased slightly from 12% to 10%.

Figure 15.9 Effects of tool rotation speed.



(Ultrasonic power = 30%; Feedrate = 0.5 mm/s; CFRP #1)

Figure 15.10 Power consumption percentage of each component under different settings of tool rotation speed.



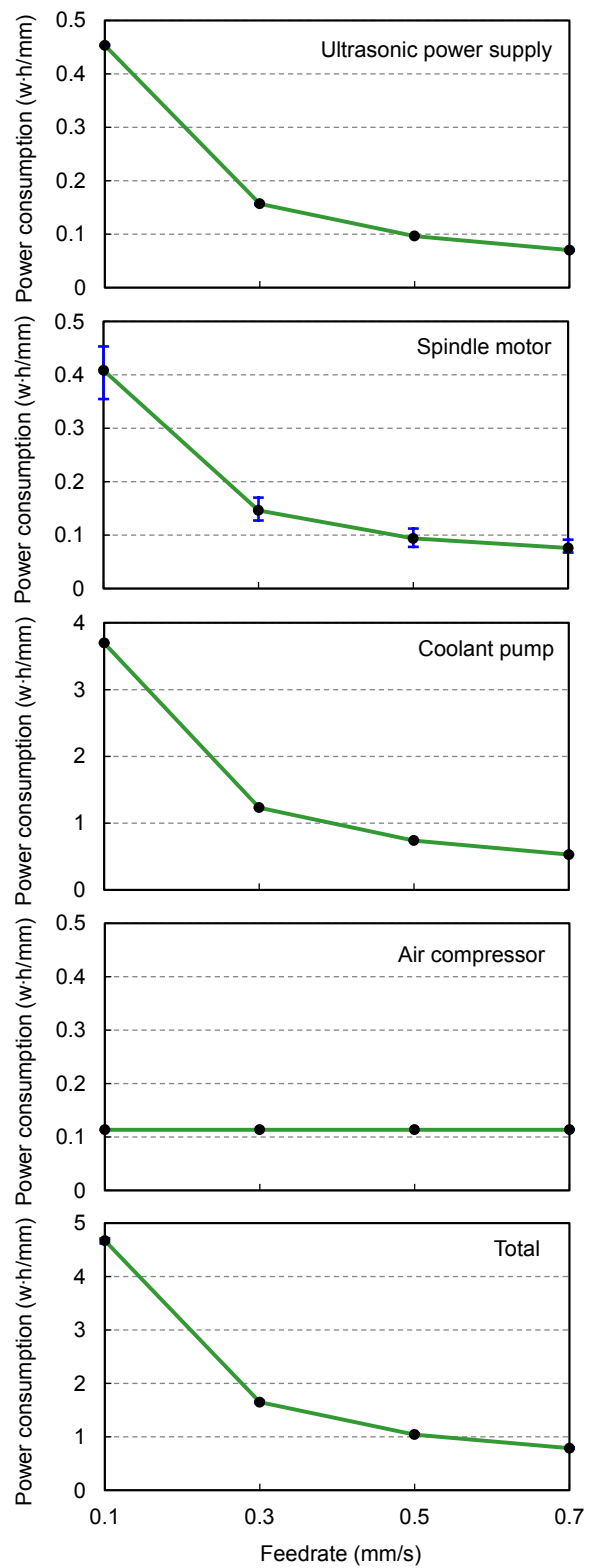
(Ultrasonic power = 30%; Feedrate = 0.5 mm/s; CFRP #1)

15.3.3 Effects of feedrate

Effects of feedrate on power consumption are shown in Figure 15.11. As feedrate increased, power consumptions of ultrasonic power supply, spindle motor, and coolant pump decreased dramatically, power consumption of air compressor kept the same, and power consumption of the entire RUM system increased remarkably.

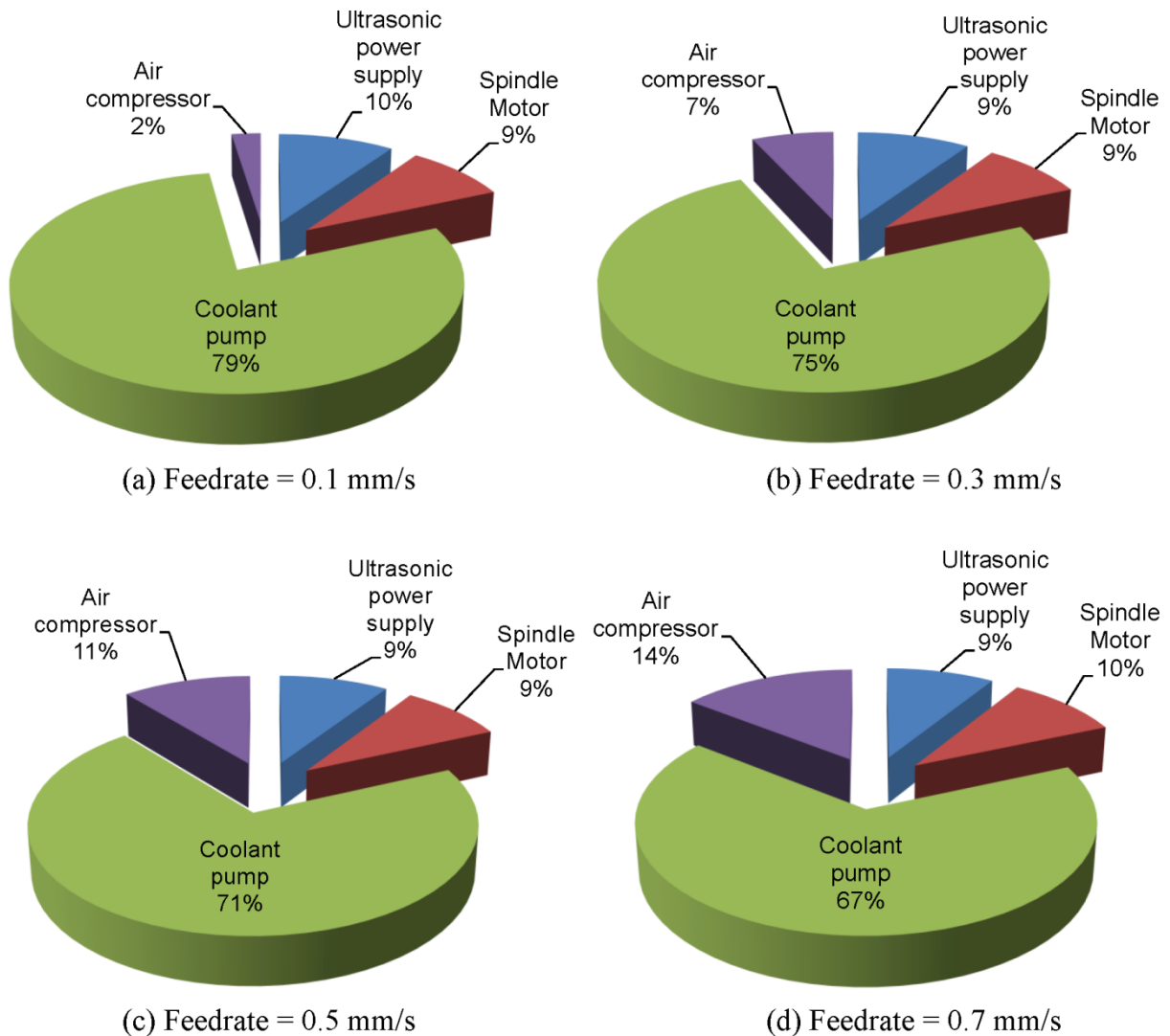
Power consumption percentages of each component under different settings of feedrate are shown in Figure 15.12. As feedrate increased from 0.1 to 0.7 mm/s, power consumption percentage of air compressor increased from 2% to 14%, power consumption percentage of coolant pump decreased from 79% to 67%, and power consumption percentages of ultrasonic power supply and spindle motor did not change much and remained as approximately 9%.

Figure 15.11 Effects of feedrate.



(Ultrasonic power = 30%; Tool rotation speed = 3000 rpm; CFRP #1)

Figure 15.12 Power consumption percentage of each component under different settings of feedrate.



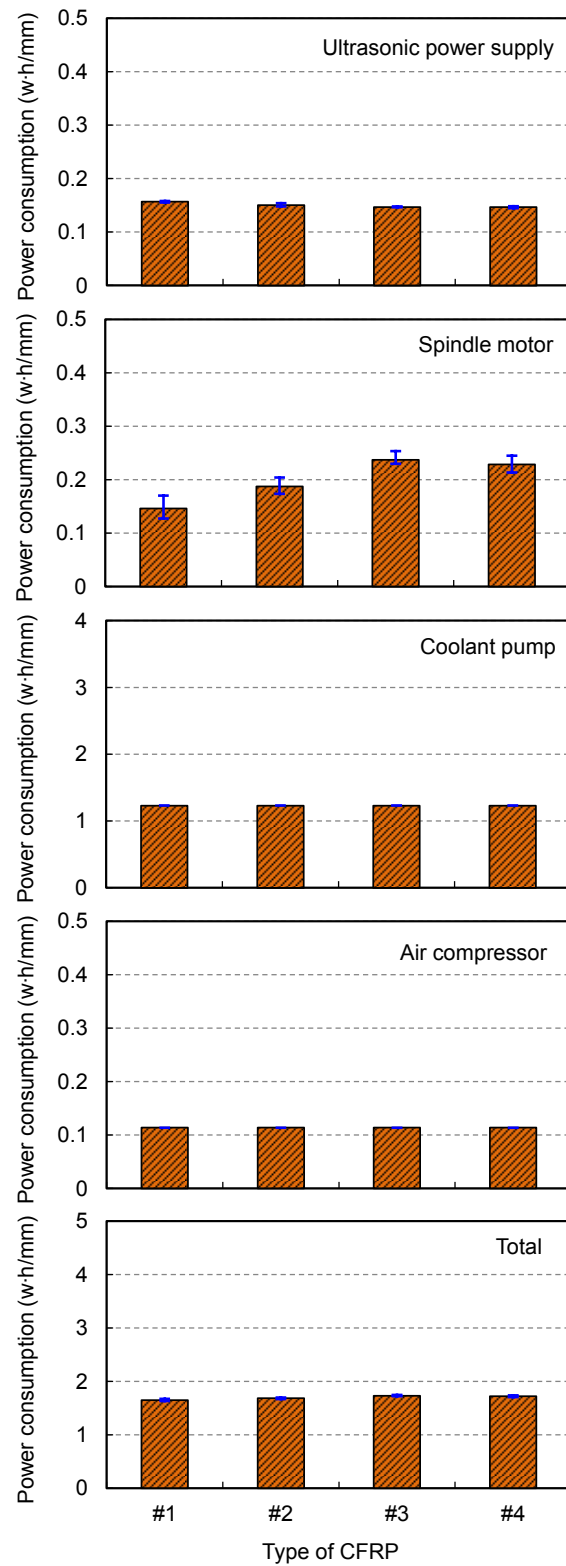
(Ultrasonic power = 30%; Tool rotation speed = 3000 rpm; CFRP #1)

15.3.4 Effects of CFRP type

Effects of CFRP type on power consumption are shown in Figure 15.13. CFRP type significantly affected power consumption of ultrasonic power supply and spindle motor. The power consumption of ultrasonic power supply was the highest when machining CFRP #1 (with wide yarn woven fiber structure) and the lowest when machining CFRP #3 (with flake fiber structure). In contrast, power consumption of spindle motor was the highest when machining CFRP #3 and the lowest when machining CFRP #1. For different types of CFRP, power consumption of coolant pump and air compressor kept unchanged. Power consumption of the entire RUM system did no change much for these different CFRP types.

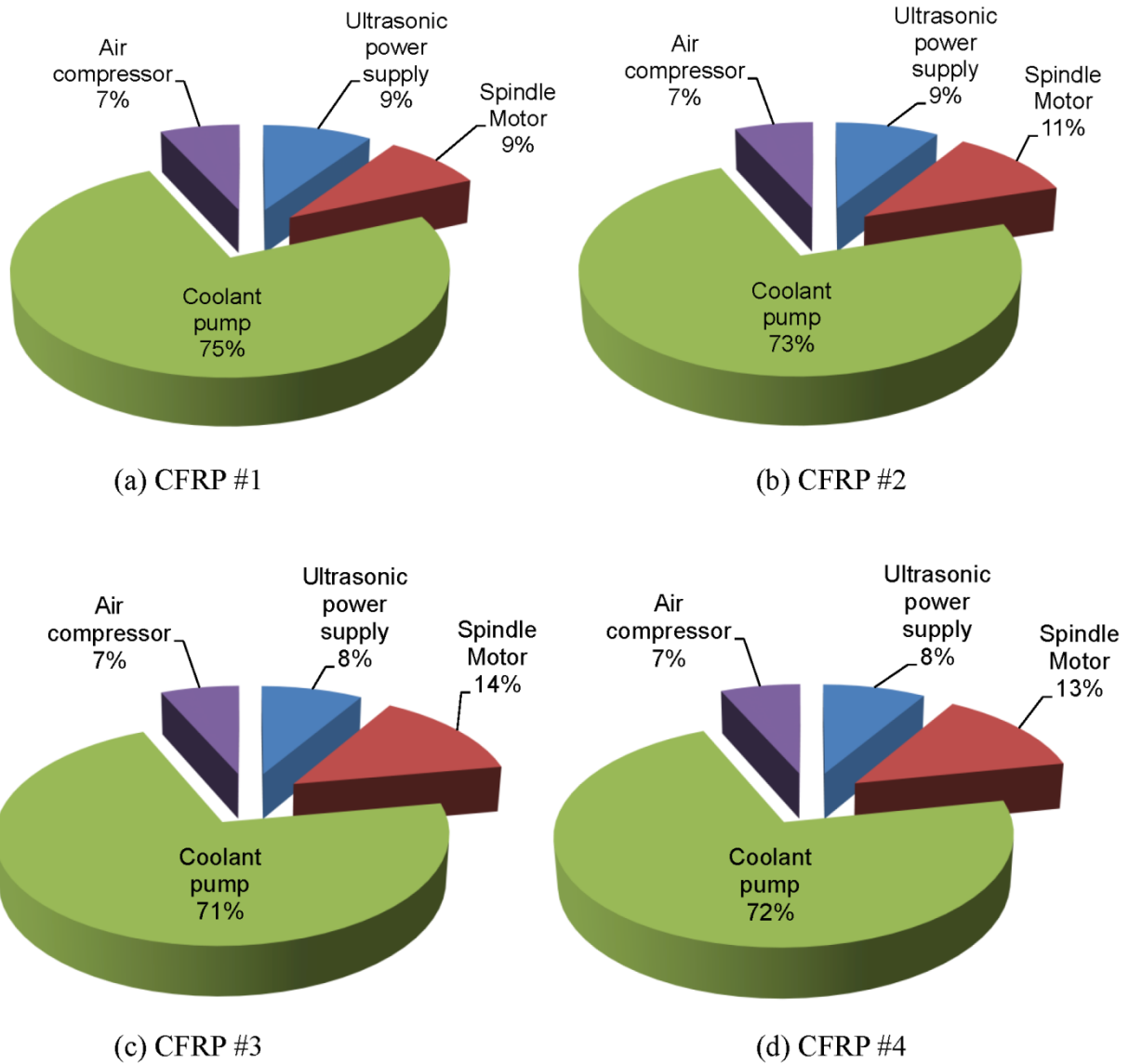
Power consumption percentages of each component for RUM of different CFRP types are shown in Figure 15.14. When CFRP type changed, power consumption of coolant pump always had the highest percentage (71% ~ 73%). Power consumption percentage of air compressor stayed at 7%. Power consumption percentages of ultrasonic power supply and spindle motor changed slightly.

Figure 15.13 Effects of CFRP type.



(Ultrasonic power = 30%; Tool rotation speed = 3000 rpm; Feedrate = 0.3 mm/s)

Figure 15.14 Power consumption percentage of each component under different CFRP type.



(Ultrasonic power = 30%; Tool rotation speed = 3000 rpm; Feedrate = 0.3 mm/s)

15.4 Conclusions

This paper reported a study on power consumption in RUM of CFRP. Power consumption of the entire RUM system and each component under different settings of

ultrasonic power, tool rotation speed, feedrate, and CFRP type was studied. The following conclusions are drawn from this study:

- (1) As ultrasonic power increased or tool rotation speed decreased, power consumption of ultrasonic power supply increased slightly, power consumption of spindle motor decreased dramatically, power consumption of coolant pump and air compressor kept unchanged, and power consumption of the entire RUM system increased slightly. As feedrate decreased, power consumptions of ultrasonic power supply, spindle motor, and coolant pump decreased dramatically, power consumption of air compressor kept the same, and power consumption of the entire RUM system increased remarkably.
- (2) CFRP type significantly affected power consumption of ultrasonic power supply and spindle motor. For different CFRP types, power consumption of coolant pump and air compressor kept unchanged. Power consumption of the entire RUM system did not change much for these different CFRP types.
- (3) Under all the test conditions, power consumption of coolant pump always had the highest percentage (higher than 65% of the entire RUM system power consumption).
- (4) As ultrasonic power increased or tool rotation speed decreased, power consumption percentage of ultrasonic power supply increased, power consumption percentage of spindle motor decreased.
- (5) As feedrate increased, power consumption percentage of air compressor increased, power consumption percentage of coolant pump decreased, and power consumption percentages of ultrasonic power supply and spindle motor did not change much.
- (6) For different CFRP types, the percentage of each component did not change much.

Acknowledgements

The work was supported by the National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to N.B.R. Diamond Tool Corp. for supplying the diamond core drills.

References

- [1] Arul S., Vijayaraghavan L., Malhotra S.K., and Krishnamurthy R., (2006), The effect of vibratory drilling on hole quality in polymeric composites, *International Journal of Machine Tools and Manufacture*, 46(3–4), pp. 252–259.
- [2] Boeing Co. web, (2011), 787 Dreamliner Program Fact Sheet, available at: <http://www.boeing.com/commercial/787family/programfacts.html>, accessed in Nov 20.
- [3] Chung D.D.L., (2010), *Composite materials science and applications*, 2nd ed. Springer-Verlag, London, UK.
- [4] Cong W.L., Feng Q., Deines T., Pei Z.J., and Treadwell C., (2011a), Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables. *Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference*, Corvallis, OR, USA.
- [5] Cong W.L., Feng Q., Deines T., Pei Z.J., and Treadwell C., (2011b), Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions, *Journal of Reinforced Plastics and Composites*, 30(10), pp. 899–906, (DOI: 10.1177/0731684411416266).
- [6] Cong, W.L., Feng, Q., Pei, Z.J., Deines, T.W., and Treadwell, C., 2012, “Rotary ultrasonic machining of carbon fiber reinforced plastic composites: using cutting fluid versus cold air as coolant,” *Journal of Composite Materials*, Vol. 46, No. 14, pp. 1745-1753. (DOI: 10.1177/0021998311424625.)

- [7] Cong, W.L., Pei, Z.J., Feng, Q., Deines, T.W., and Treadwell, C., 2012, “Rotary ultrasonic machining of CFRP: a comparison with twist drilling,” *Journal of Reinforced Plastics and Composite*, Vol. 31, No. 5, pp. 313-321. (DOI: 10.1177/0731684411427419)
- [8] Davim J.P. and Reis P., (2003), Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, *Mater Design*, 24(5), pp. 315–324.
- [9] Feng, Q., Cong, W.L., Pei, Z.J., and Ren, C.Z., 2012, “Rotary ultrasonic machining of carbon fiber reinforced polymer: feasibility study,” *Machining Science and Technology*, Vol. 16, No. 3, pp. 380-398.
- [10] Guu Y.H., Hocheng H., Tai N.H., and Liu S.Y., (2001), Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, *Journal of Materials Science*, 36(8), pp. 2037–2043.
- [11] Lambert B.K., (1987), Cutting and drilling of composite materials, *Carbide Tool Journal*, 19, pp. 31–34.
- [12] Li Z.C., Pei Z.J., Sisco T., Micale A.C., and Treadwell C., (2007), Experimental study on rotary ultrasonic machining of graphite/epoxy panel. *Proceedings of the ASPE 2007 Spring Topical Meeting on Vibration Assisted Machining Technology*, Chapel Hill, NC, USA, pp. 52–57.
- [13] Mallick P.K., (1997), *Composite Engineering Handbook*, Marcel Dekker Inc., New York, NY, USA.
- [14] Mangalgiri P.D., (1999), Composite materials for aerospace applications, *Bulletin of Materials Science*, 22(3), pp. 657–664.
- [15] Morgan P., (2005), *Carbon fibers and their composites*, CRC Press, Taylor & Francis Group, Boca Raton, FL, USA.

- [16] Park K.Y., Choi J.H., and Lee D.G., (1995), Delamination-free and high efficiency drilling of carbon fiber reinforced plastics, *Journal of Composite Materials*, 29(15), pp. 1988–2002.
- [17] Ruegg C.H. and Habermeier J., (1981), Composite propeller shafts: design and optimization, *Automot Eng-UK*, 6, pp. 13–15.
- [18] Sadat A.B., (1995), Delamination and other types of damage of graphite/epoxy composite caused by machining, *Machining of Advanced Materials - Presented at ASME Summer Meeting at University of California*, Vol. 208, Los Angeles, AMD, MD-Vol. 59, pp. 41–52.
- [19] Schwartz M.M., (1992), *Composite materials handbook*, 2nd ed. Columbus, McGraw-Hill, OH, USA.

Chapter 16 - CFRP - A Study on Cutting Temperature

Paper title:

Rotary ultrasonic machining of CFRP composites: a study on cutting temperature

Published in:

Journal of Reinforced Plastics and Composite (2012), Vol. 31, No. 22, pp. 1516-1525.

Authors' names:

W.L. Cong¹, Xiaotian Zou², T.W. Deines¹, Nan Wu³, Xingwei Wang^{2, 3}, and Z.J. Pei¹

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
2. Department of Biomedical Engineering and Biotechnology, University of Massachusetts Lowell, MA 01854, USA
3. Department of Electrical and Computer Engineering, University of Massachusetts Lowell, MA 01854, USA

Abstract

Carbon fiber reinforced plastic (CFRP) composites are used in many applications due to their superior properties. Drilling is the most frequently used machining process due to the need for assembly of CFRP parts in mechanical structures. Rotary ultrasonic machining (RUM) has been successfully used in drilling CFRP composites. Reported investigations on RUM of CFRP cover several output variables (including cutting force, torque, surface roughness, material removal rate, fiber delamination, tool wear, and power consumption). However, there are no reported studies on cutting temperature in RUM of CFRP. This paper presents an experimental study on cutting temperature in RUM of CFRP using two measurement methods (thermocouple and fiber optic sensor). Comparisons between these two methods are made and relations between input variables (ultrasonic power, tool rotation speed, and feedrate) and cutting temperature are experimentally determined.

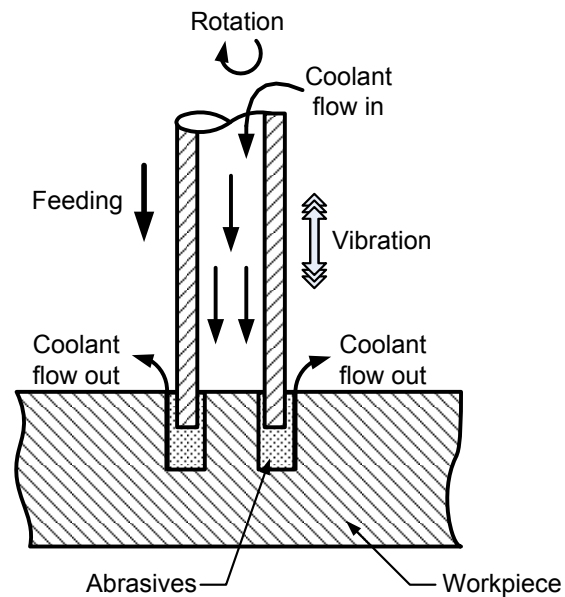
Keywords: Carbon fiber reinforced plastic (CFRP) composite, Cutting temperature, Drilling, Fiber optic sensor, Grinding, Rotary ultrasonic machining, Thermocouple.

16.1 Introduction

Carbon fiber reinforced plastic (CFRP) composites are used in many applications due to their superior properties. Drilling is the most frequently used machining process due to the need for assembly of CFRP parts in mechanical structures. Rotary ultrasonic machining (RUM) has been successfully used in drilling CFRP [Li et al. 2007; Cong et al. 2011abc, Feng et al. 2011, Cong et al. 2012]. RUM is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. Figure 16.1 illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During machining, the rotating tool vibrates axially at an ultrasonic frequency (typically 20 kHz) and feeds along its

axial direction towards the workpiece. Coolant is pumped through the core of the cutting tool, washes away the swarf, and keeps cutting zone cool.

Figure 16.1 Illustration of rotary ultrasonic machining.



There are reported studies on RUM of CFRP. Effects of input variables (including ultrasonic power, tool rotation speed, feedrate, and coolant type) on output variables (including cutting force, torque, surface roughness, material removal rate, fiber delamination, tool wear, and power consumption) have been investigated [Li et al. 2007; Cong et al. 2011abc, Feng et al. 2011, Cong et al. 2012]. Cutting temperature has long been recognized as an important factor affecting the machining process [Krishnaraj et al, 2005; Chen 1997]. Cutting temperature in RUM (using titanium as workpiece) has been investigated [Cong et al., 2011]. However, there are no reported studies on cutting temperature in RUM of CFRP. High cutting temperature in RUM of CFRP could cause many problems, such as burning of machined surface and higher tool wear rate. Burning of machined surface results in higher surface roughness and lower strength around the

drilled hole. Higher tool wear rate results in larger cutting force and torque as well as shorter tool life. Therefore, it is important to study cutting temperature in RUM of CFRP.

Reported measurement methods of cutting temperature in drilling include thermocouple (including tool-work thermocouple and commercial thermocouple) [Li and Shih 2007, DeVries et al. 1976], thermal paint [Koch and Levi 1971], powder and film [Kato et. al. 1976, Walton et. al. 2006], pyrometer [Lin et. al. 1992, Ueda et. al. 1998], infrared camera [Muller-Hummel and Lahres 1994, Dorr et. al. 2003], and fiber optic sensor [Ueda et. al. 2007]. After comparison of available methods, commercial thermocouple and fiber optic sensor methods were selected to measure cutting temperature in this study. The thermocouple method has low cost and is easy to install. However, they might be insensitive to small or transient temperature changes and susceptible to noise [Shiraishi 1988]. The fiber optic sensor method may overcome these disadvantages, but the fiber optic sensors are very brittle and require special demodulation instrument.

This paper, for the first time, reports an experimental investigation on cutting temperature in RUM of CFRP. It compares two temperature measurement methods and investigates effects of input variables (ultrasonic power, tool rotation speed, and feedrate) on cutting temperature. The paper is organized into four sections. Following this introduction section, Section 16.2 describes experimental set-up and conditions, workpiece material properties, and measurement procedures. Section 16.3 presents and discusses experimental results. Finally, conclusions are summarized in Section 16.4.

16.2 Experimental set-up and conditions

16.2.1 Workpiece

The workpiece was carbon fiber reinforced plastic (CFRP) composite. It was made through the artificial combination of two different materials: carbon fibers and polymer. The carbon fibers provided the strength and stiffness, while the polymer (epoxy matrix) served as the binder material to protect fiber and transfer load. Plain woven fabric of carbon fibers with an orientation of 0/90 degrees was used, as illustrated in Figure 16.2. The carbon fiber yarns in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The workpiece contained 42 layers of carbon fabrics. The workpiece size was 200 mm × 150 mm × 16 mm. Workpiece material properties are listed in Table 16.1 Workpiece material properties..

Figure 16.2 Fiber structures of CFRP.

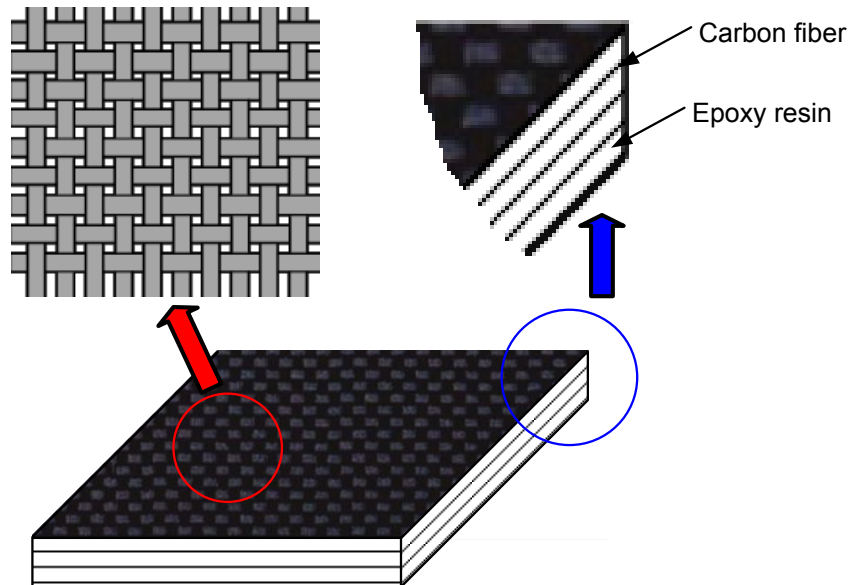


Table 16.1 Workpiece material properties.

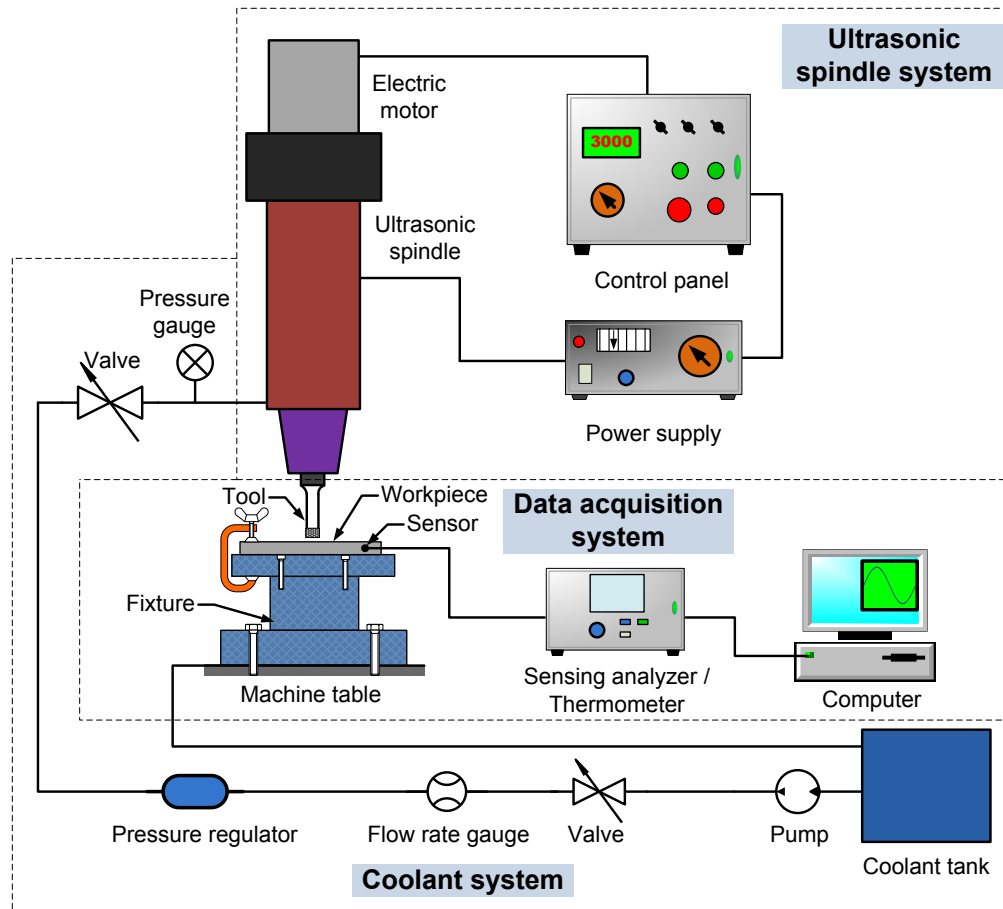
Property	Unit	Value
Density of CFRP	kg/m ³	1550
Hardness (Rockwell)	HRB	70-75
Density of epoxy matrix	kg/m ³	1200
Elastic modulus of epoxy matrix	GPa	4.5
Tensile strength of epoxy matrix	MPa	130
Poisson's ratio of epoxy matrix		0.2
Density of carbon fiber	kg/m ³	1800
Elastic modulus of carbon fiber	GPa	230
Tensile strength of carbon fiber	GPa	5
Poisson's ratio of carbon fiber		0.3

16.2.2 Experimental set-up

The experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental setup is schematically illustrated in Figure 16.3. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system was comprised of an ultrasonic spindle, a power supply, and an electric motor. The power supply converted (60 Hz) electrical supply to high-frequency (20 kHz) electrical energy. This high-frequency electrical energy was provided to a piezoelectric converter (located inside the ultrasonic spindle) that changed high-frequency electrical energy into mechanical vibration. The ultrasonic vibration was amplified and transmitted to the cutting tool, causing the cutting tool to vibrate at the frequency of 20 kHz. The amplitude of ultrasonic vibration could be adjusted by changing the setting of output control of the power supply. The motor attached atop the ultrasonic spindle supplied the rotational motion of the tool. Different speeds were obtained by adjusting the motor speed controller on the control panel. The data acquisition system was used for measurement of cutting temperature. More details about this

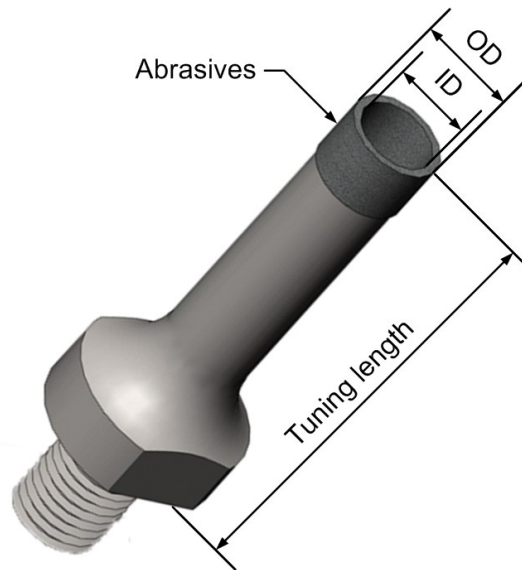
system will be described in Section 2.3 (measurement procedures). The coolant system was comprised of coolant tank, pump, pressure regulator, flow rate and pressure gauges, and valves. The coolant system provided coolant to the ultrasonic spindle and the cutting interface.

Figure 16.3 Illustration of experimental set-up.



The cutting tool, as illustrated in Figure 16.4, was metal-bonded diamond core drill (NBR Diamond Tool Corp., LaGrangeville, NY, USA). The outer and inner diameters (OD and ID) of the cutting tool were 9.54 mm and 7.82 mm, respectively, and the tuning length was 45 mm. The diamond abrasives had a mesh size of 80/100 and concentration of 100. The metal bond was of B type.

Figure 16.4 Illustration of a metal-bonded diamond core drill.



The following input variables were varied in the experiments:

- Ultrasonic power: Percentage of power from ultrasonic power supply (higher ultrasonic power would produce larger ultrasonic vibration amplitude);
- Tool rotation speed: Rotational speed of cutting tool;
- Feedrate: Feedrate of cutting tool.

The values of these input variables are listed in Table 16.2. The pressure and flow rate of coolant were kept constant at 40 psi and 1.5 lpm, respectively.

Table 16.2 Input variables and their values.

Variable	Value
Ultrasonic power (%)	0; 20; 40; 60
Tool rotation speed (rpm)	1000; 2000; 3000; 4000
Feedrate (mm/s)	0.1; 0.3; 0.5

No replications were carried out in this study because of the following reasons. The first reason was that, based on a previous study on temperature measurements in RUM of titanium where replications were carried out under each test condition [Cong et al., 2011] and preliminary experimental data, variations of measured temperature under the same test condition were small (less than 5 °C) in comparison to differences in measured temperatures under different levels of input variables.

16.2.3 Measurement procedure

Temperature measurement is illustrated in Figure 16.5. A blind hole (with a diameter of 1.5 mm) perpendicular to the tool feeding direction and along the radius direction of the hole was drilled into the workpiece. The distance between the end of this blind hole and the cylindrical surface of the machined hole was 0.5 mm. A K-type thermocouple (Model SC-GG-K-30-36, Omega Engineering, Inc., Stamford, CT, USA) and a fiber optic sensor were positioned inside the blind hole and touched the end of blind hole. To fix the thermocouple and the fiber optic sensor, the opening of the blind hole was sealed with plasticene. Waterproof gel was coated on the plasticene to keep cutting fluid from entering the hole. The signals from the thermocouple were collected by a digital thermometer (HH147U, Omega Engineering Inc., Stamford, CT, USA). The signals from the fiber optic sensor were demodulated through an optical sensing analyzer (OSA Si720, Micron Optics, Atlanta, GA, USA). The digital data were recorded and displayed on a computer using software (MatLab 7.13, MathWork Crop., Natick, MA, USA). The sampling rates for both measurement methods were set at 1 Hz.

The thermocouple method is based on the principle of thermoelectric effect (Seebeck effect) [Van Herwaarden and Sarro, 1986]. A thermocouple was composed of two dissimilar metals (For example, K-type was composed of chromel and alumel) that were jointed together by

melting and solidification (without adding a third material) to form a “hot” end. The other end was called “cold” end. Changes of temperature at the “hot” end would cause changes of electric potential (voltage) between two dissimilar metals at the “cold” end. According to the relationship between temperature at the “hot” end and electric potential at the “cold” end, temperature could be obtained by measuring electric potential.

Figure 16.5 Illustration of temperature measurement.

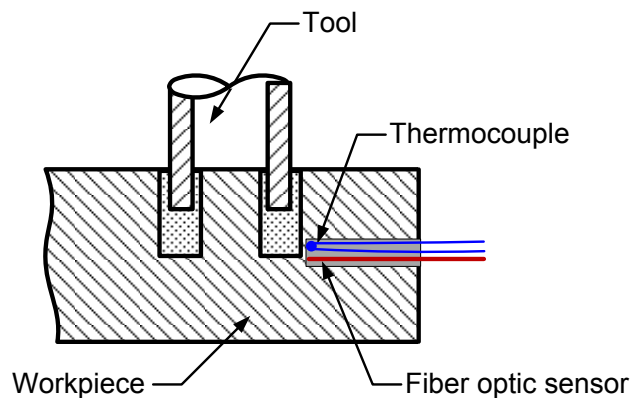
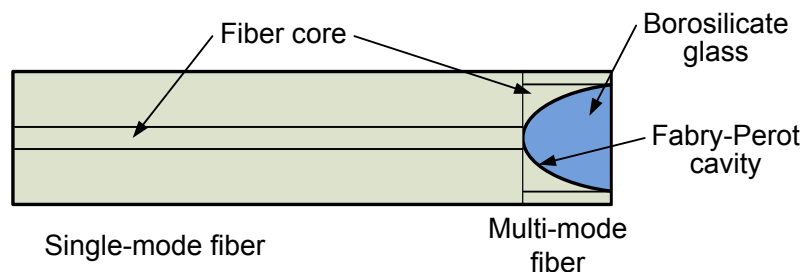


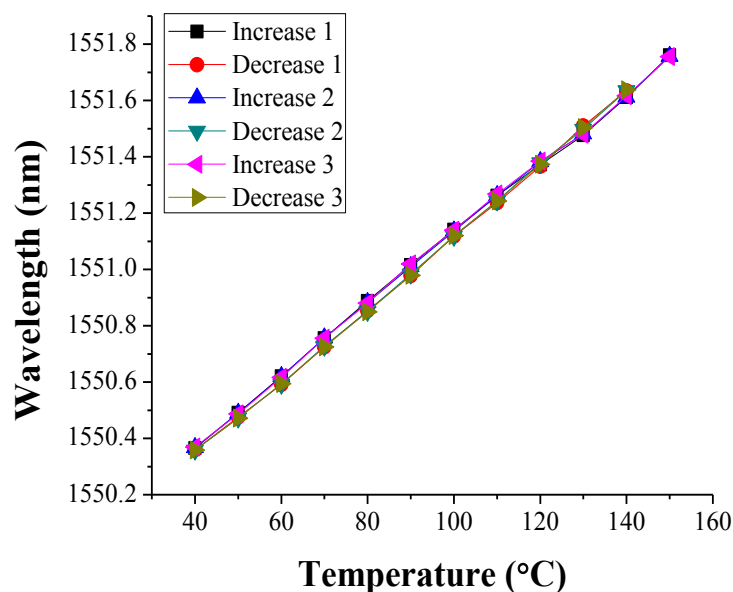
Figure 16.6 The structure of the fiber optic sensor.



The fiber optic sensor method is based on the Fabry-Perot (FP) principle. A schematic diagram of the fiber optic sensor is shown in Figure 16.6. The fiber optic sensor consisted of a piece of single-mode fiber, a piece of multi-mode fiber, and a piece of borosilicate glass. When an incident light illuminated on the FP structure, the light reflected on two interfaces. One

interface was between the fiber core and the borosilicate glass. The other was between the polished side of borosilicate glass and the air. The two reflection lights interfered with each other and would generate an interference pattern. The interference pattern would shift according to the change of the distance between the two interfaces, which were called FP cavity length. The FP cavity length would change due to the expansion of borosilicate glass caused by temperature change. The change of the FP cavity length would lead change of laser scan wavelength. By interrogating the interference pattern shift, the temperature information could be acquired. The spectrum response from the reflected light was collected and analyzed by the OSA. The recorded data from the fiber optic sensor was laser signal scan wavelength (from 1520 to 1570 nm with a resolution of 2.5 pm). Before measurement, fiber optic sensors were calibrated by using a temperature calibrator (T400, E Instrument, Langhorne, PA, USA) to obtain the relationship between wavelength and temperature. During the calibration process, the calibrator temperature range was set from 40 °C to 150 °C. The calibration data of the sensors are shown in Figure 16.7.

Figure 16.7 The relationship between wavelength and cutting temperature.



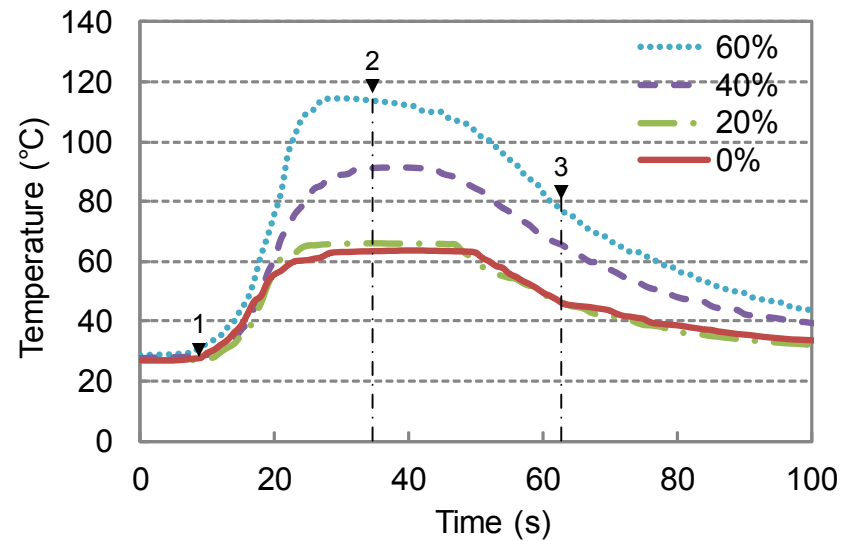
It is important to note that the temperature measured in this study is not the cutting temperature at the interface between workpiece material and tool working surface (i.e. the end surface of the tool). For RUM, it is difficult to directly measure the cutting temperature at this cutting interface. For example, it is difficult to fix any sensor very close to the cutting interface since the tool rotates at a high speed. The measured temperature should be lower than the temperature at the cutting interface. However, the measured temperature has a certain relationship with the interface temperature. The authors are developing simulation models to estimate the interface temperature from the temperature data measured in this study.

16.3 Results and discussion

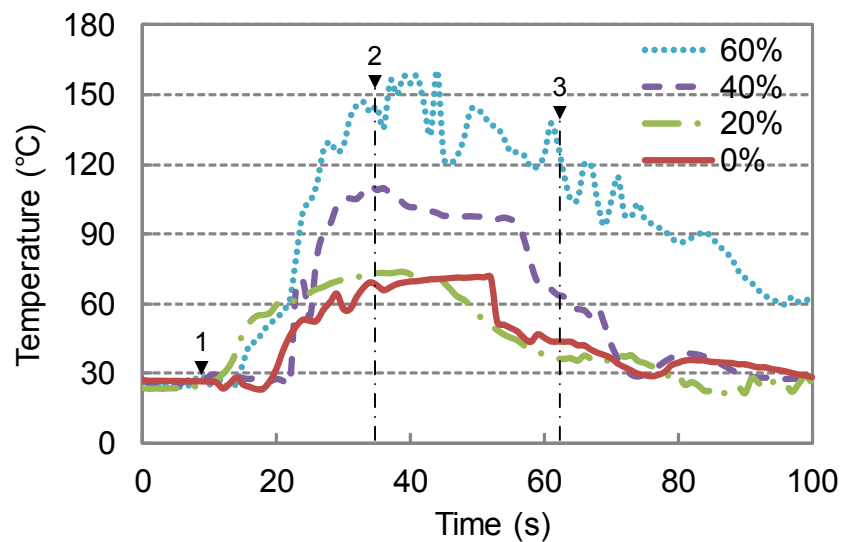
16.3.1 Effects of ultrasonic power

Cutting temperature versus machining time curves under different levels of ultrasonic power for both methods are shown in Figure 16.8. Labels 1, 2, and 3 in Figure 16.8 (as well as Figure 16.10 and Figure 16.12) indicated when the cutting tool started cutting the workpiece, when the end face of the cutting tool passed through the measured position, and when the cutting tool cut through the workpiece thickness. The temperature-time curves obtained by the thermocouple method were smoother than those obtained by the fiber optic sensor method. The fiber optic sensor method was more sensitive to temperature than the thermocouple method. The maximum cutting temperatures measured by the thermocouple method were located between 20 and 40 s on the temperature-time curve. However, the maximum cutting temperatures measured by the fiber optic sensor method were located between 30 s and 50 s on the temperature-time curve.

Figure 16.8 Cutting temperature versus machining time for different levels of ultrasonic power. (Tool rotation speed = 3000 rpm; Feedrate = 0.3 mm/s)



(a) Thermocouple



(b) Fiber optic sensor

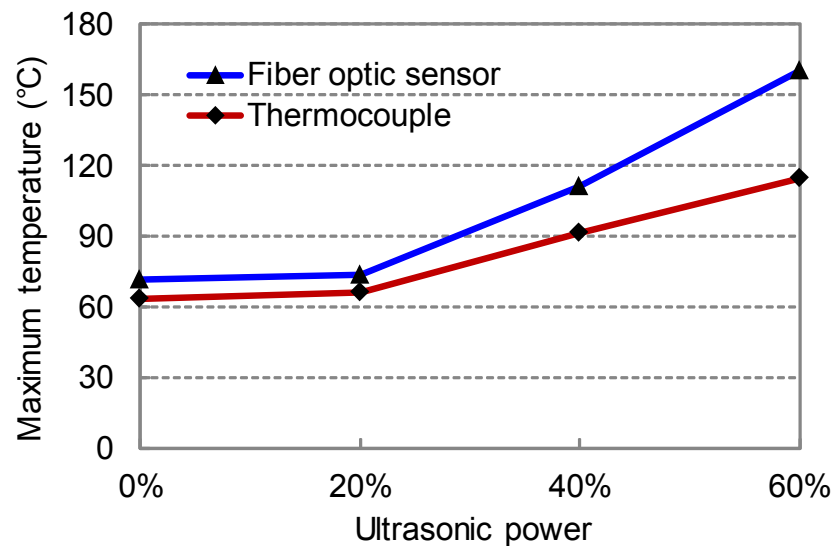
- 1: The cutting tool started cutting the workpiece;
- 2: The end face of the cutting tool passed through the measured position;
- 3: The cutting tool cut through the workpiece thickness.

Effects of ultrasonic power on maximum cutting temperature are illustrated in Figure 16.9. In Figure 16.9 (as well as Figure 16.11 and Figure 16.13), the data points are the maximum

values on the temperature-time curve. When ultrasonic power changed from 0 to 20%, maximum cutting temperature did not change much for both methods. When ultrasonic power increased from 20% to 60%, maximum cutting temperature dramatically increased. This trend is different from observations reported for RUM of titanium by Cong et al. [2011]. They found that, in RUM of titanium, cutting temperatures when ultrasonic vibration was on (ultrasonic power = 20%, 40%, and 60%) were lower than those when ultrasonic vibration was off (ultrasonic power = 0%). When ultrasonic power increased from 20% to 60%, there was an obvious (but not dramatic) increase in cutting temperature. Compared with those measured by the thermocouple method, cutting temperatures measured by the fiber optic sensor method were higher, especially, when ultrasonic power was high. At this point in time, the authors did not fully understand why there existed relatively big differences in measured temperature between the thermocouple and fiber optic sensor methods. However, they had several hypotheses in mind and will conduct further research to test them. The authors noticed larger fluctuations in measure temperature by the fiber optic sensor method. One possible reason is that the measuring point (its size was of micrometers) of the fiber optic sensor was much smaller than that (its size was of millimeters) of the thermocouple. Smaller measurement point was more sensible to the change of temperature. The authors plan to conduct further investigations to understand the large temperature fluctuations.

Ultrasonic power determines vibration amplitude. As ultrasonic power increases, the vibration amplitude will increase [Cong et al., 2011d]. This will increase the penetration depth of diamond grains into the workpiece material, increasing the interaction force between the diamond grain and the workpiece material [Liu et al., 2012]. This could result in an increase of cutting temperature.

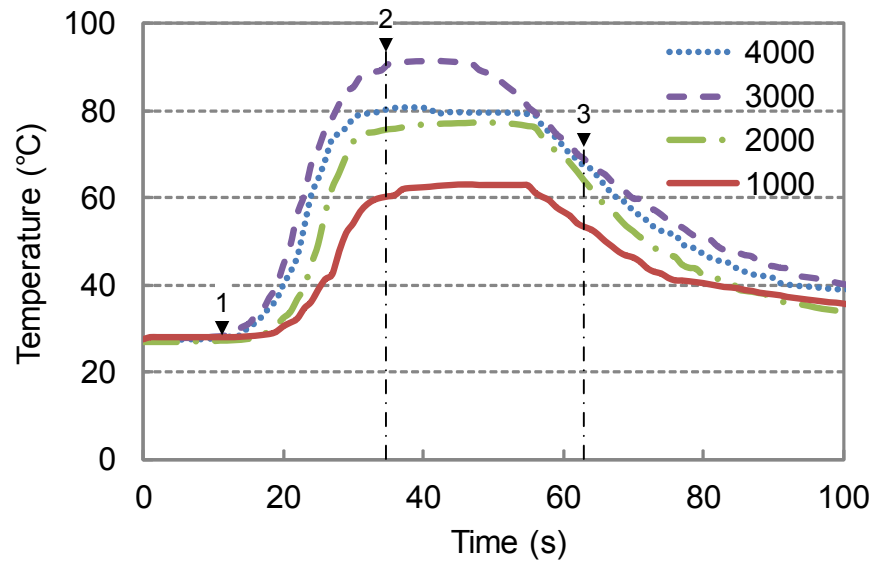
Figure 16.9 Effects of ultrasonic power on maximum cutting temperature.
(Tool rotation speed = 3000 rpm; Feedrate = 0.3 mm/s)



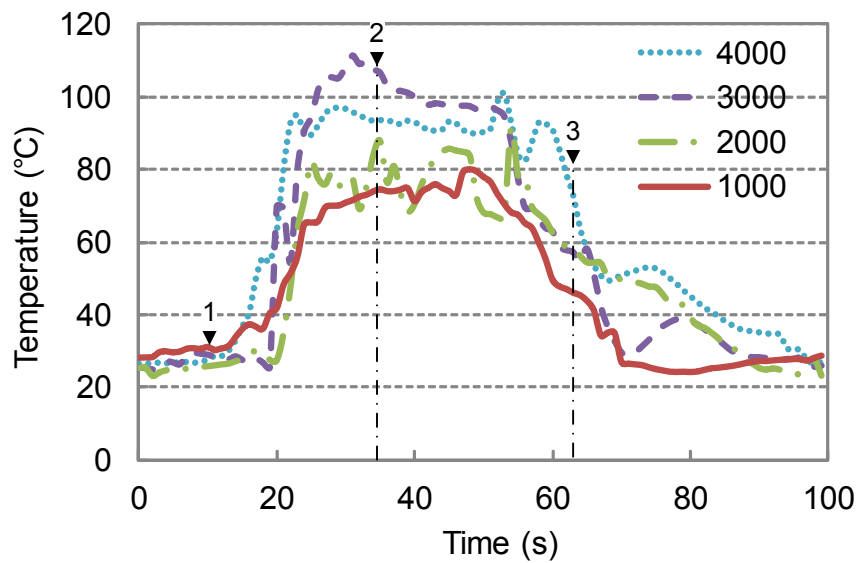
16.3.2 Effects of tool rotation speed

Cutting temperature versus machining time curves under different levels of tool rotation speed for both methods are shown in Figure 16.10. The temperature-time curves obtained by the thermocouple method were smoother than those obtained by the fiber optic sensor method. The maximum cutting temperatures measured by the thermocouple method were located between 20 and 40 s. However, the maximum cutting temperatures measured by the fiber optic sensor method for different levels of tool rotation speed were located in different time.

Figure 16.10 Cutting temperature versus machining time for different levels of tool rotation speed. (Feedrate = 0.3 mm/s; Ultrasonic power = 40%)



(a) Thermocouple

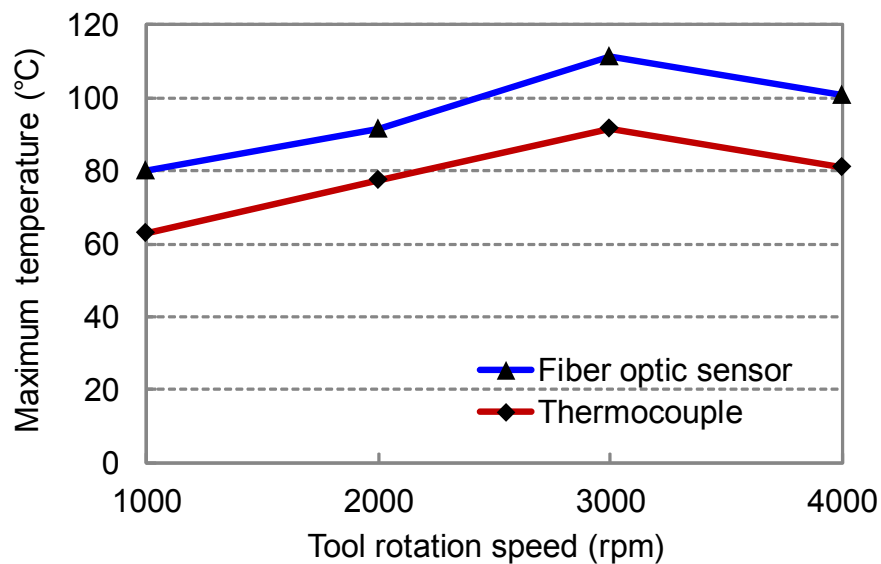


(b) Fiber optic sensor

- 1: The cutting tool started cutting the workpiece;
- 2: The end face of the cutting tool passed through the measured position;
- 3: The cutting tool cut through the workpiece thickness.

Effects of tool rotation speed on maximum cutting temperature are shown Figure 16.11. It can be seen that, when tool rotation speed increased from 1000 to 3000 rpm, maximum cutting temperature increased. However, further increase of tool rotation speed from 3000 to 4000 rpm led to decrease of maximum cutting temperature. Compared with that measured by the thermocouple method, maximum cutting temperature measured by the fiber optic sensor method was higher by about 20 °C under each level of tool rotation speed. This trend is different from observations reported for RUM of titanium by Cong et al. [2011]. They found that, in RUM of titanium, cutting temperature decreased sharply as tool rotation speed increased from 1500 to 3000 rpm, but gradually increased as tool rotation speed increased from 3000 to 6000 rpm.

Figure 16.11 Effects of tool rotation speed on maximum cutting temperature.
(Feedrate = 0.3 mm/s; Ultrasonic power = 40%)



When feedrate was kept the same, increase of tool rotation speed would lead to increase of sliding distance between diamond and workpiece within a fixed period of time [Churi et al. 2006 and Liu et al., 2012]. This might be the reason why cutting temperature increased as tool

rotation speed increased from 1000 to 3000 rpm. Compared with 3000 rpm, tool rotation speed of 4000 rpm caused a lower depth of cut for individual diamond grains on the tool end face, leading to lower cutting force [Churi et al. 2006], which might cause temperature to decrease.

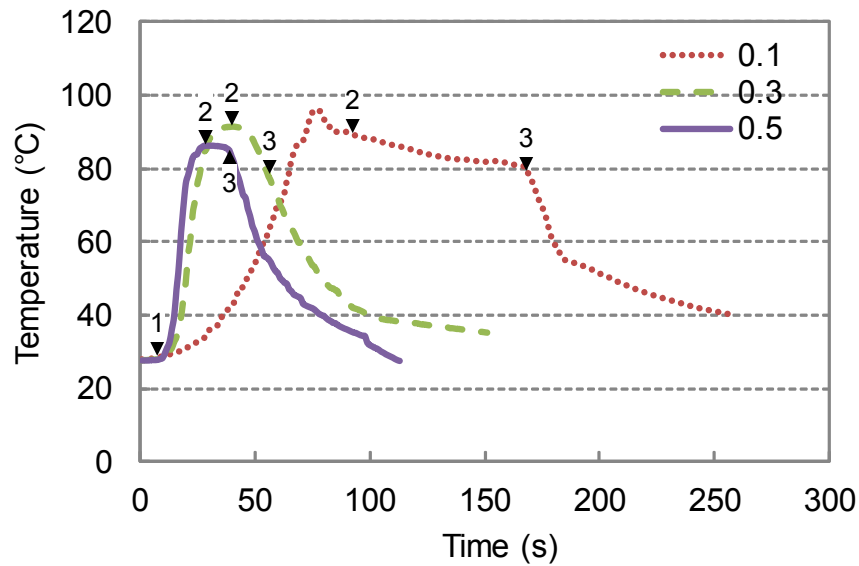
16.3.3 Effects of feedrate

Cutting temperature versus machining time curves under different levels of feedrate for both methods are shown in Figure 16.12. The temperature-time curves obtained by the thermocouple method were smoother than those obtained by the fiber optic sensor method. For both methods, the maximum cutting temperatures for different levels of feedrate (0.1, 0.3, and 0.5 mm/s) were located around 75, 40, and 30 s on the temperature-time curves, respectively.

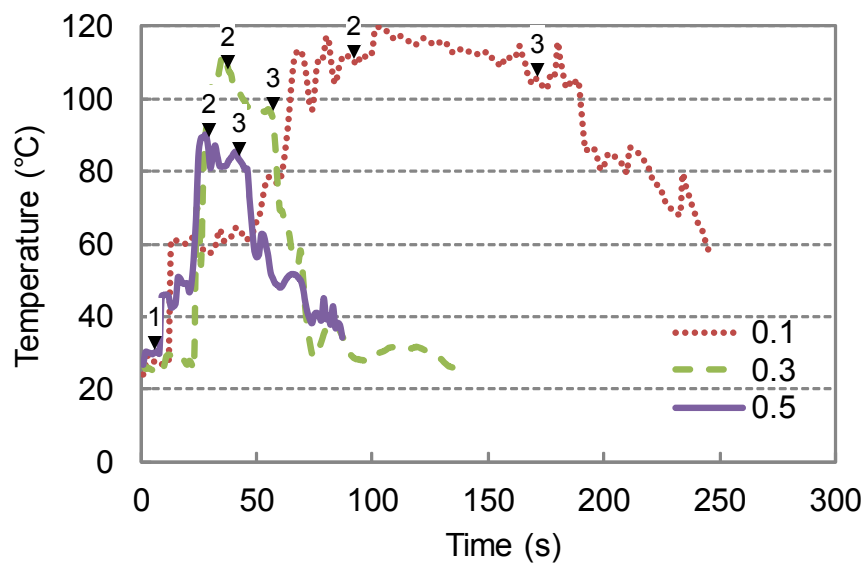
Effects of feedrate on maximum cutting temperature are shown in Figure 16.13. As feedrate increased, maximum cutting temperature decreased for both methods. Compared with that measured by the thermocouple method, cutting temperature measured by the fiber optic sensor method was higher. Also, as feedrate increased, the differences between the temperature measurements by the two methods decreased. This trend is different from observations reported for RUM of titanium by Cong et al. [2011]. They found that, in RUM of titanium, when feedrate changed from 0.02 mm/s to 0.04 mm/s, there was nearly no change in cutting temperature. However, when the feedrate increased from 0.04 mm/s to 0.06 mm/s, cutting temperature increased dramatically.

When tool rotation speed was kept the same, lower feedrate led to longer grinding time which would generate more heat. This might be the reason for the higher temperature when feedrate was lower.

Figure 16.12 Cutting temperature versus machining time for different levels of feedrate.
(Tool rotation speed = 3000 rpm; Ultrasonic power = 40%)



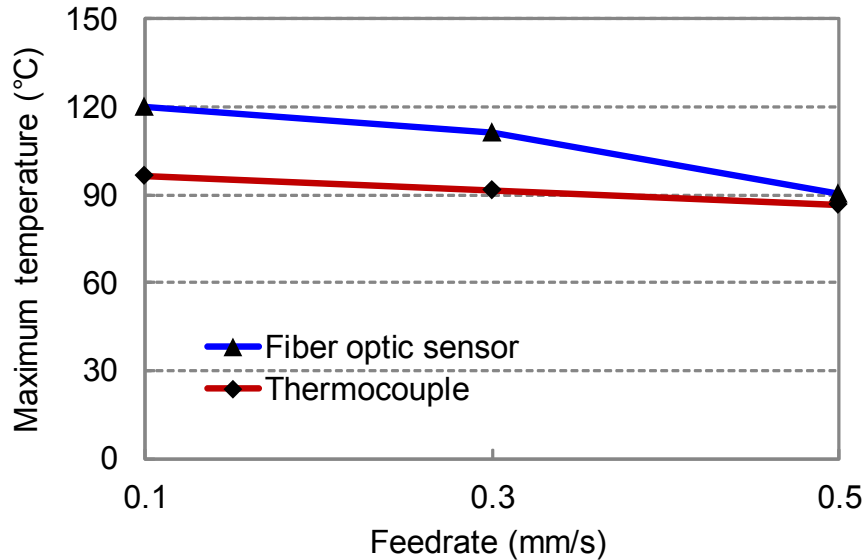
(a) Thermocouple



(b) Fiber optic sensor

- 1: The cutting tool started cutting the workpiece
- 2: The end face of the cutting tool passed through the measured position
- 3: The cutting tool cut through the workpiece thickness

Figure 16.13 Effects of feedrate on maximum cutting temperature. (Tool rotation speed = 3000 rpm; Ultrasonic power = 40%)



16.4 Conclusions

This paper, for the first time, reported an experimental study on cutting temperature in RUM of CFRP. It presented effects of three machining variables (ultrasonic power, tool rotation speed, and feedrate) on cutting temperature. The following conclusions can be drawn:

Maximum cutting temperature decreased as ultrasonic power and feedrate decreased. As tool rotation speed increased, maximum cutting temperature firstly increased and then decreased.

Temperatures measured by the fiber optic sensor method were higher than those measured by the thermocouple method. In the other words, FP fiber optic sensors provide more accurate localized measurement in RUM than thermocouples. One of the possible reasons is that the thermocouple sensed the average temperatures inside the blind hole, and subjected to heat flow disturbances.

Due to limitations of these two measurement methods (position sensors inside the blind hole near the machined surface), the temperatures measured in this paper were not the cutting

temperatures at the tool-workpiece interface. The measured temperatures should be significantly lower than those at the interface. Nevertheless, the experimental results were still valuable. It is reasonable to assume that these input variables will have similar effects on the temperature at the tool-workpiece interface. Furthermore, the experimentally determined relations between input variables and cutting temperature can provide foundations for attempts to develop simulation models to predict cutting temperatures at the tool-workpiece interface.

Acknowledgements

The work was supported by National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to N.B.R. Diamond Tool Corp. for supplying the diamond core drill and Sonic-mill, Inc. for providing technical support.

References

- [1] Arul S, Vijayaraghavan L, Malhotra SK, and Krishnamurthy R, (2006) The effect of vibratory drilling on hole quality in polymeric composites, *International Journal of Machine Tools and Manufacture*, 46(3-4), pp. 252-259.
- [2] Chen WC, (1997) Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates, *International Journal of Machine Tools and Manufacture*, 37(8), pp. 1097-1108.
- [3] Chung DDL, (2010) *Composite materials science and applications*, 2nd edn, Springer-Verlag, London, UK.
- [4] Churi NJ, Pei ZJ, Treadwell C, (2006) Rotary ultrasonic machining of titanium alloy: effects of machining variables. *Machining Science and Technology*, 10(3), pp. 301-321.

- [5] Cong WL, Feng Q, Deines T, Pei ZJ, and Treadwell C, (2011) Experimental study on cutting temperature in rotary ultrasonic machining, *Proceedings of NAMRI/SME*, Vol. 39, pp. 369-376.
- [6] Cong WL, Feng Q, Deines T, Pei ZJ and Treadwell C., (2011a) Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables. *Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference*, Corvallis, OR, USA.
- [7] Cong WL, Feng Q, Deines T, Pei ZJ and Treadwell C, (2011b) Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions, *Journal of Reinforced Plastics and Composites*, 30(10), pp.899-906.
- [8] Cong, WL, Feng Q, Pei, ZJ, Deines, TW, and Treadwell, C, (2011c) Rotary ultrasonic machining of carbon fiber reinforced plastic composites: using cutting fluid versus cold air as coolant, *Journal of Composite Materials*, doi: 10.1177/0021998311424625.
- [9] Cong, WL, Pei, ZJ, Mohanty, N, Van Vleet, E, and Treadwell, C, (2011d) Vibration amplitude in rotary ultrasonic machining: a novel measurement method and effects of process variables, *Journal of Manufacturing Science and Engineering*, 133(3), pp. 034501–1-034501–6.
- [10] Cong, WL, Feng Q, Pei, ZJ, Deines, TW, and Treadwell, C, (2012) Rotary ultrasonic machining of CFRP: a comparison with twist drilling, *Journal of Reinforced Plastics and Composite*, 31(5), pp. 313-321.
- [11] Davim JP and Reis P, (2003) Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, *Materials and Design*, 24(5), pp. 315-324.
- [12] Feng, Q, Cong, WL, Pei, ZJ, and Ren, CZ, (2011) Rotary ultrasonic machining of carbon

fiber reinforced polymer: feasibility study, accepted to appear in *Machining Science and Technology*.

- [13] Guu YH, Hocheng H, Tai NH, and Liu SY, (2001) Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, *Journal of Materials Science*, 36(8), pp. 2037-2043.
- [14] Krishnaraj V, Vijayarangan S, Mohamed Nazrudeen M, and Suresh G, (2005) Analysis of temperature rise in drilling of GFRP composites material with various drill profiles, 21st AIMTDR Conference, Dec 21-24, 2004, Vellore Institute of Technology, Vellore, India.
- [15] Lambert BK, (1987) Cutting and drilling of composite materials, *Carbide Tool Journal*, Vol. 19, pp. 31-34.
- [16] Li ZC, Pei ZJ, Sisco T, Micale AC, and Treadwell C, (2007) Experimental study on rotary ultrasonic machining of graphite/epoxy panel, *Proceedings of the ASPE 2007 Spring Topical Meeting on Vibration Assisted Machining Technology*, Chapel Hill, NC, USA, pp. 52-57.
- [17] Liu, DF, Cong, WL, Pei, ZJ, and Tang, YJ, (2012) A cutting force model for rotary ultrasonic machining of brittle materials, *International Journal of Machine Tools and Manufacture*, 52(1), pp. 77-84.
- [18] Mallick PK, (1997) *Composite Engineering Handbook*, Marcel Dekker Inc., New York, NY, USA.
- [19] Morgan P, (2005) *Carbon Fibers and Their Composites*, CRC Press, Taylor & Francis Group, Boca Raton, FL, USA.
- [20] Park KY, Choi JH, and Lee DG, (1995) Delamination-free and high efficiency drilling of

- carbon fiber reinforced plastics, *Journal of Composite Materials*, 29(15), pp. 1988-2002.
- [21] Ruegg CH and Habermeier J, (1981) Composite propeller shafts: design and optimization. *Automotive Engineering UK*, Vol. 6, pp. 13-15.
- [22] Sadat AB, (1995) Delamination and other types of damage of graphite/epoxy composite caused by machining, *Machining of Advanced Materials - Presented at ASME Summer Meeting at University of California, Los Angeles, CA, USA*, pp. 41-52.
- [23] Schwartz MM, (1992) *Composite Materials Handbook*, 2nd edn., McGraw-Hill, Columbus, OH, USA.
- [24] Shiraishi, M, (2003) Scope of in-process measurement, monitoring and control techniques in machining processes — Part 1: In-process techniques for tools, *Precision Engineering*, 10(4), pp. 179-189.
- [25] Tangaev IA, (1975) Power consumption of roller-bit drilling as an index of the mining-related properties of the solid rock, *Soviet Mining Science*, 11(1), pp. 74-77.
- [26] Van Herwaarden AW and Sarro PM, (1986) Thermal sensors based on the Seebeck effect, *Sensors and Actuators*, 10(3-4), pp. 321-346.

Chapter 17 - CFRP - A Mechanistic Predictive Model on Cutting Force

Paper title:

Rotary ultrasonic machining of CFRP: a mechanistic predictive model for cutting force

Submitted to:

Ultrasonics

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, and Zhang, C.L.²

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

2. The State Key Laboratory of Tribology, Department of Precision Instruments and Technology, Tsinghua University, Beijing 100084, China

Abstract

Cutting force is one of the most important output variables in rotary ultrasonic machining (RUM) of carbon fiber reinforced plastic (CFRP) composites. Many experimental investigations on cutting force in RUM of CFRP have been studied. However, in the literature, there are no reported studies on cutting force model on RUM of CFRP. This paper develops a mechanistic predictive model for cutting force in RUM of CFRP. The material removal mechanism of CFRP in RUM is analyzed first. The model is based on the assumption that brittle fracture is the dominant mode of material removal. The model is mechanistic in the sense that fracture volume factor K_V can be obtained by a few experiments for a particular CFRP material and then used in prediction of cutting force over a wide range of input variables. CFRP micromechanical analysis is conducted to represent CFRP as an equivalent homogeneous material to obtain the mechanical properties of CFRP from its components. Based on this model, the relationships between input variables (including ultrasonic vibration amplitude, tool rotation speed, feedrate, abrasive size, and abrasive concentration) and cutting force are predicted. The relationships between input variables and important intermediate variables (indentation depth, effective contact time, and max impact force of single abrasive grain) are investigated to explain these predicted trends of cutting force. Experiments are conducted to verify the model, and experimental results agree well with predicted trends from this model.

Keywords: Rotary ultrasonic machining, CFRP, Mechanistic predictive model, Cutting force.

17.1 Introduction

17.1.1 Introduction of carbon fiber reinforced plastic (CFRP) composites

Carbon fiber reinforced plastic (CFRP) composites have strong carbon fibers surrounded by a weak polymer matrix. The carbon fibers are to support the load. The matrix serves to distribute, hold, and protect the fibers and also to transmit the load to the fibers [Gay et al., 2003; Tong et al., 2002; Chung 2010].

CFRP composites have many superior properties including low density (lower than aluminum), high strength (as strong as high-strength steels), high stiffness (stiffer than titanium), good fatigue resistance, good creep resistance, low friction coefficient, good wear resistance, good toughness and damage tolerance, good corrosion resistance, good dimensional stability (about zero coefficient of thermal expansion), and high vibration damping ability [Arul et al., 2006; Sadat, 1995; Davim and Reis, 2003; Lambert, 1987; Sadat, 1995; Guu et al., 2001; Chung, 2010; Mallick, 1997; Schwartz, 1992; Morgan, 2005; Park et al. 1995; Ruegg and Habermeier 1981].

Due to their superior properties, CFRP composites are attractive for a variety of applications. They are used in many types of structures including aircraft, spacecraft, automobiles, ships, bridges, athletic equipment, and leisure goods. They are employed in engine blades, power transmission shafts, machine spindles, robot arms, pressure vessels, and chemical containers [Park et al., 1995; Ruegg and Habermeier, 1981; Gay et al., 2003; Guu et al., 2001; Arul et al., 2006; Sadat, 1995].

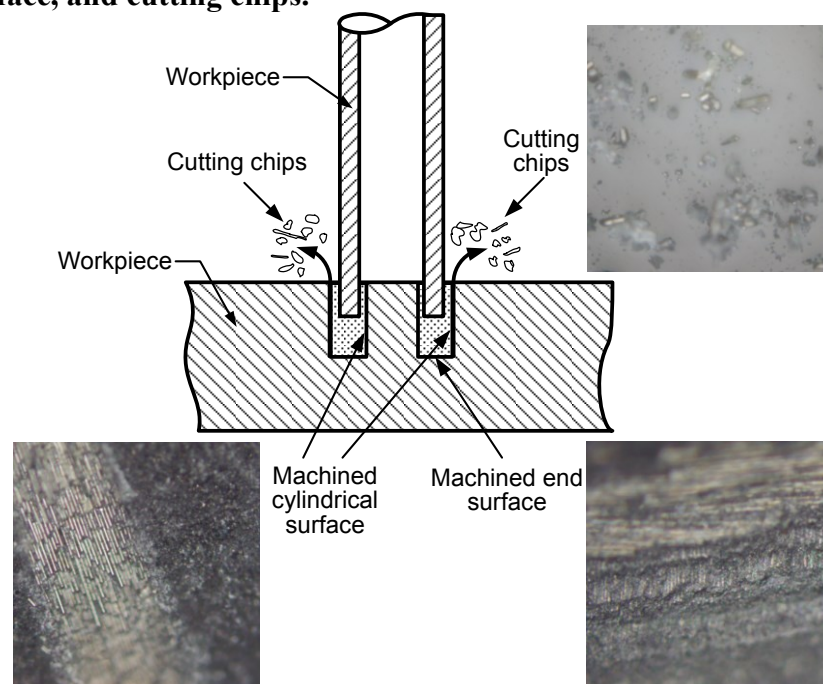
A large number of holes need to be drilled in CFRP in many applications (especially in aircraft assembling) [Boeing Co. Web; Enemuoh et al., 2001; Tsao and Hocheng, 2005; Chung,

2010; Gay et al., 2003]. Because of their superior properties, CFRPs are very difficult to machine. Therefore, it is important to develop cost-effective drilling processes.

17.1.2 Introduction of rotary ultrasonic machining

Rotary ultrasonic machining (RUM) has been used to drill CFRP successfully [Li et al. 2007; Cong et al. 2011ab; Cong et al., 2012abc; Feng et al. 2012]. RUM is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. Figure 17.1 illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During machining, the rotating tool vibrates axially at an ultrasonic frequency (typically 20 kHz) and feeds along its axial direction towards the workpiece. Coolant is pumped through the core of the cutting tool, washing away the swarf and preventing the cutting zone from overheating.

Figure 17.1 Illustration of RUM and microscope pictures of machined cylindrical surface, machined end surface, and cutting chips.



17.1.3 Reported investigations on RUM of CFRP

The reported investigations on RUM of CFRP are primarily focused on comparisons of twist drilling and RUM, effects of input variables on output variables, studies of feasible regions using cold air as coolant, and comparisons of different cooling conditions (cold air and cutting fluid). [Li et al. 2007; Cong et al. 2011ab; Cong et al., 2012abc; Feng et al. 2012]. However, in the literature, there are no reported studies on cutting force model in RUM of CFRP.

17.1.4 Purposes of the paper

In this paper, a mechanistic predictive model for cutting force in RUM of CFRP is developed. To identify the material removal mechanism in RUM of CFRP, an analysis is conducted first. It is found that material removal in RUM of CFRP is dominated by brittle fracture. CFRP micromechanical analysis is conducted to represent CFRP as an equivalent homogeneous material to achieve the CFRP mechanical properties from the properties of its individual components. In this mechanistic model, a proportionality parameter (fracture volume factor, K_V) will be used to describe the ratio between summation of material removal rates of all abrasive particles on the cutting tool end face and the theoretical material removal rate. The model is mechanistic in the sense that this parameter for a particular workpiece material is a constant and can be obtained from a few experiments and then be used in the prediction of cutting force over a wide range of input variables. Based on this model, the influences of input variables (including ultrasonic vibration amplitude, tool rotation speed, feedrate, abrasive size, and abrasive concentration) on cutting force can be predicted. The relationships between input variables and some important intermediate variables (indentation depth, effective contact time, and max impact force of single abrasive grain) have been investigated to explain these predicted trends of cutting force. The experiments are conducted to verify the model.

This paper is organized into six sections. After this introduction part, cutting force model development process is described in Section 17.2. Section 17.3 presents the process to obtain the proportionality parameter (fracture volume factor, K_V). The predicted influences of input variables (including tool rotation speed, feedrate, ultrasonic vibration amplitude, abrasive concentration, and abrasive size) on cutting force (as well as some important intermediate variables) are shown in Section 17.4. Model verification by pilot experiments is provided in Section 17.5. Conclusions are drawn in Section 17.6.

17.2 Model development

17.2.1 Approach to model development

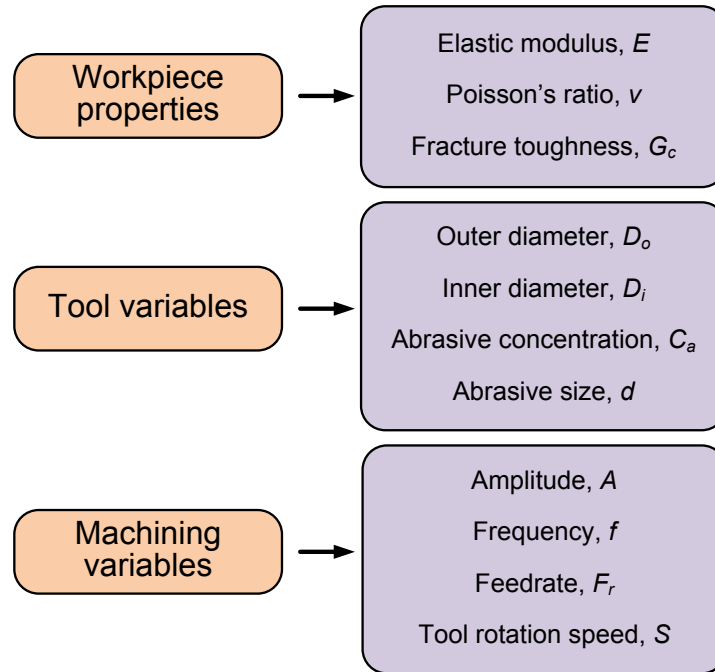
RUM can be considered as a combination of ultrasonic machining process and abrasive grinding process. There are two principal approaches for RUM model development: (1) ultrasonic machining is considered as predominant process and (2) rotation motion of the cutting tool is considered as predominant process [Pei et al., 1995b]. The first approach has been successfully used in RUM model development [Zhang et al., 2011; Liu et al., 2012; Qin et al., 2011; Qin et al., 2009; Pei and Ferreira, 1998; Pei et al., 1995b] and is employed in this study. This study starts from an analysis of one particle and then sums up the effects of all active abrasive particles taking part in cutting. The model development includes the following steps:

- (1) Analyze the CFRP material removal mechanism;
- (2) Establish a relation between cutting force and abrasive particle indentation depth;
- (3) Achieve the CFRP mechanical properties (Elastic modulus, Poisson's ratio, and fracture toughness) using composite micromechanical analysis;

- (4) Estimate the volume of material removed by one abrasive particle in a single ultrasonic vibration cycle;
- (5) Establish a cutting force model by aggregating the effects of all active abrasive particles.

The variables in development of RUM cutting force model for CFRP include tool variables, workpiece properties, and machining variables, as listed in Figure 17.2.

Figure 17.2 Input variables in development of RUM cutting force model for CFRP.



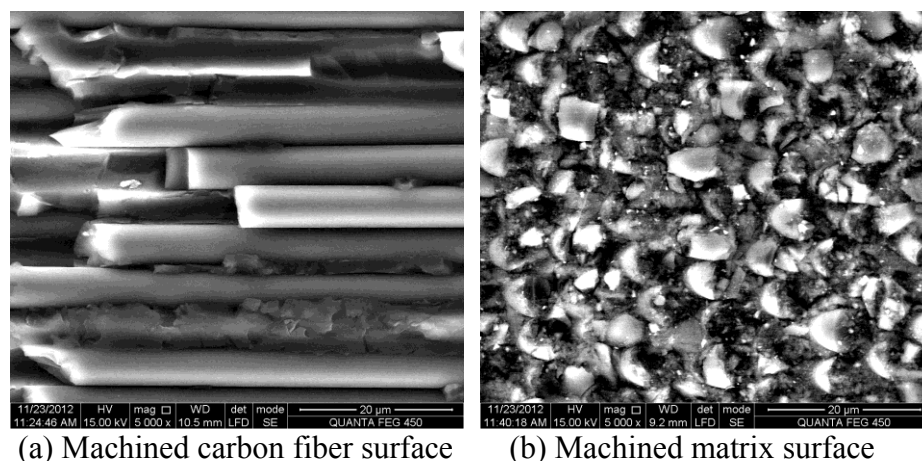
17.2.2 CFRP material removal mechanism analysis

For CFRP's components (fiber and matrix), carbon fiber is a brittle material and thermoset matrix (for example, epoxy) is brittle and has low fracture toughness value [Matthews et al., 2003; Gay et al., 2003]. Machining of composite materials should be based on brittle fracture and chip separation occurs by brittle fracture rather than plastic deformation [Lazar, 2012]. Many experimental or theoretical investigations have been conducted on drilling of CFRP

using diamond core drill [Hocheng and Tsao, 2005; Dharan 1978; Hocheng and Tsao, 2006; Tsao, 2006; Tsao and Chiu, 2011]. The CFRP material removal principle used in these studies is brittle fracture.

The material removal mechanisms in RUM of ceramics include brittle fracture and ductile removal [Pei and Ferreira, 1998, Pei et al., 1995ab]. To analyze CFRP material removal mechanism in RUM, the topographies of CFRP machined cylindrical surface, machined end surface, and cutting chips were observed by microscope (Model BX51 Olympus Inc. Tokyo, Japan). Figure 17.1 and Figure 17.3 show microscope pictures on machined cylindrical surface, machined end surface, and cutting chips. It could be seen that machined cylindrical surface, machined end surface, and cutting chips were generated by fracture mode of material removal. The chipping or spalling of the workpiece material could be seen from the machined cylindrical and end surfaces. The chips were formed by brittle fracture. It can be concluded that the material removal mechanisms in RUM of CFRP were brittle fracture.

Figure 17.3 SEM pictures of machined surface.



17.2.3 Assumptions in model development

Major assumptions for CFRP micromechanical analysis in the model development include:

- (1). The bond between fibers and matrix is perfect;
- (2). The elastic moduli and diameters of fibers and space between fibers are uniform;
- (3). The fibers are continuous and parallel;
- (4). The fibers and matrix follow Hooke's law (linearly elastic);
- (5). The fibers have uniform strength; and
- (6). The composite is free of voids.

Similar assumptions were used by other researcher [Hocheng and Tsao, 2005; Dharan 1978; Hocheng and Tsao, 2006; Tsao, 2006; Tsao and Chiu, 2011] in developing force model for grinding (core drill) of CFRP.

Other assumptions for RUM of CFRP in the model development include:

- (1). Workpiece material is an ideally brittle material (for the ideally brittle material, on plastic deformation is present);
- (2). The material is removed by brittle fracture (the material is removed by the propagation and intersection of cracks ahead of and around the cutting tool or abrasive particles);
- (3). The diamond particles are rigid spheres of the same size;
- (4). All diamond abrasive particles on the end face of a cutting tool have the same height and all of them participate in cutting during each ultrasonic cycle.

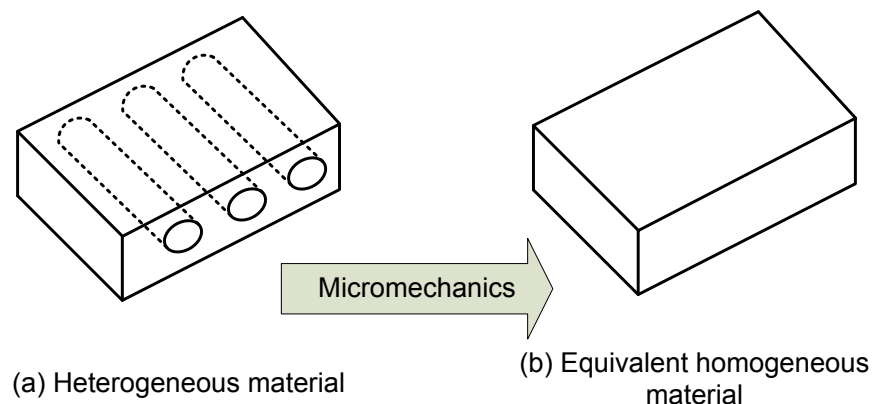
Additional assumptions and simplifications will be presented later when they are used.

17.2.4 CFRP micromechanical analysis (strength of materials approach)

“Micromechanics are the study of composite materials taking into account the interaction of the constituent materials in detail. Micromechanics allow the designer to represent a heterogeneous material (its properties vary from point to point) as an equivalent homogeneous material (it has the same properties everywhere), usually isotropic” [Barbero, 2010; Kaw, 2006], as illustrated in Figure 17.4.

Micromechanics process has been used to predict stiffness with great success. The stiffness of an isotropic material is completely described by two properties including the elastic modulus E and Poisson's ratio ν . Using micromechanics process, the fracture toughness can also be obtained. There are several approaches used to derive micromechanics including (1) Strength of materials approach; (2) Semi-Empirical models; and (3) Elasticity approach [Barbero, 2010; Kaw, 2006]. The strength of materials approach is the simplest and most intuitive approach and is employed in this study.

Figure 17.4 Micromechanics process (After [Barbero, 2010]).



17.2.5 Relationship between indentation depth and maximum impact force

During RUM, cutting tool feeds into workpiece at a certain feedrate and vibrates up and down ultrasonically. The cutting tool is not in continuous contact with workpiece due to its ultrasonic vibration. In each ultrasonic cycle, each abrasive grain on the end face of cutting tool will make contact with the workpiece for a certain period of time (effective contact time, Δt). When penetration of an abrasive grain reaches the maximum depth, maximum impact force (F_1) for one abrasive grain penetrating workpiece is produced.

The indentation depth, is the maximum depth to which abrasive grains penetrate the workpiece surface, can be calculated by [Timoshenko and Goodier, 1970]

$$\delta = \left[\frac{9}{16} \frac{(F_i / n)^2}{d / 2} \left(\frac{1 - \nu_d^2}{E_d} + \frac{1 - \nu^2}{E} \right)^2 \right]^{1/3} \quad (17.1)$$

Since the elastic modulus of diamond is much larger than that of workpiece ($E_d \gg E$), the equation can be simplified as [Pei et al., 1995b]

$$\delta = \left[\frac{9}{16} \frac{(F_i / n)^2}{d / 2} \left(\frac{1 - \nu^2}{E} \right)^2 \right]^{1/3} \quad (17.2)$$

where,

F_i is maximum contact force between tool and workpiece, N;

n is the number of active abrasive grains on the end face of cutting tool;

d is the size of abrasive grains (average diameter of abrasive grains), mm;

E is the elastic modulus of workpiece material, MPa;

ν is the Poisson's ratio of workpiece material.

Please note that E and ν used in Equations 17.1 and 17.2 are for CFRP composite material. E and ν of each CFRP components (carbon fiber and epoxy) are known. Section 2.6 estimates E and ν of CFRP from those of carbon fiber and epoxy.

By Equation 17.2, the maximum impact force between tool and workpiece can be expressed as

$$F_i = \frac{8^{1/2} n E d^{1/2} \delta^{3/2}}{3(1-\nu^2)} \quad (17.3)$$

The maximum impact force for one abrasive grain is

$$F_1 = \frac{F_i}{n} = \frac{8^{1/2} E d^{1/2} \delta^{3/2}}{3(1-\nu^2)} \quad (17.4)$$

Number of active abrasive grains on the end face of cutting tool can be determined by [Liu et al., 2011]

$$n = \left[\frac{0.88 \times 10^{-3}}{(\pi/6)d^3 \rho} \frac{C_a}{100} \right]^{\frac{2}{3}} A_0 = \left[\frac{0.88 \times 10^{-3}}{(\pi/6) \times 100} \right]^{\frac{2}{3}} \left(\frac{C_a}{d^3 \rho} \right)^{\frac{2}{3}} A_0 = 6.561 \times 10^{-4} \left(\frac{C_a}{d^3 \rho} \right)^{\frac{2}{3}} A_0 \quad (17.5)$$

where,

C_a is the abrasive concentration;

ρ is the density of abrasive material, g/mm³, $\rho = 3.52 \times 10^{-3}$ g/mm³ for diamond;

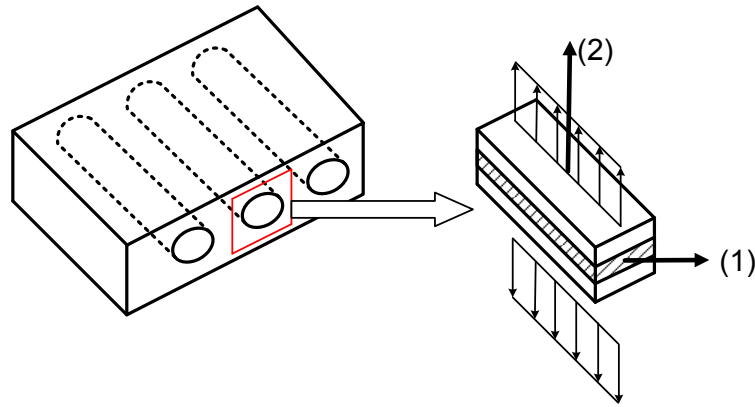
A_0 is the area of the cutting tool end face, mm², $A_0 = \pi(D_o^2 - D_i^2)/4$, (D_o and D_i are the outer and inner diameters of cutting tool, respectively, mm).

17.2.6 Elastic modulus and Poisson's ratio

Elastic modulus and Poisson's ratio are different in longitudinal and transverse directions of the fiber. In RUM of CFRP, the machining load is applied on transverse direction of the fiber. The elastic modulus and Poisson's ratio of CFRP in the fiber transverse direction should be used

in model development. To calculate these two properties in transverse direction, those in longitudinal direction need to be calculated first. For simplicity, there is an assumption that a cylindrical fiber is treated as a rectangular one, as illustrated in Figure 17.5. In reality, most micromechanics formulations do not represent the actual geometry of the fiber at all [Barbero, 2010; Kaw, 2006].

Figure 17.5 Cylindrical fiber simplification method.



Rule of mixtures (ROM) formula [Barbero, 2010; Kaw, 2006] is used to predict the elastic modulus of CFRP in the fiber longitudinal direction (E_1)

$$E_1 = E_f V_f + E_m V_m \quad (17.6)$$

where

E_f is the elastic modulus of fiber material in CFRP;

E_m is the elastic modulus of matrix material in CFRP;

V_f is the volume fraction of the fiber which can be calculated by $V_f = \frac{\text{volume of fiber}}{\text{total volume}}$;

V_f is the volume fraction of the matrix which can be calculated by

$$V_m = \frac{\text{volume of matrix}}{\text{total volume}}.$$

There is an assumption in this formulation which states that strains in the longitudinal direction of the fibers are the same as those in the matrix [Barbero, 2010; Kaw, 2006].

The Poisson's ratio of CFRP composite materials in the longitudinal direction is

$$\nu_{12} = \nu_f V_f + \nu_m V_m \quad (17.7)$$

where ν_f is Poisson's ratio of fiber material in CFRP and ν_m is Poisson's ratio of matrix material in CFRP.

Inverse rule of mixtures (IROM) formula [Barbero, 2010; Kaw, 2006] is used to determine the elastic modulus of CFRP in the fiber transverse direction (fiber perpendicular to the loading) (E_2)

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \quad (17.8)$$

The main assumption of this determination is that the stress is the same in the fiber and the matrix. This assumption is needed to maintain equilibrium in the transverse direction and implies that the fiber-matrix bond is perfect [Barbero, 2010; Kaw, 2006].

The elastic modulus used in this model is

$$E = E_2 = \frac{E_f E_m}{V_f E_m + V_m E_f} \quad (17.9)$$

There is a relationship between elastic modulus and Poisson's ratio in different direction

$$\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j} \quad (\text{with } i \neq j) \quad (17.10)$$

In this case, the Poisson's ratio in transverse direction can be calculated by

$$\nu = \nu_{21} = \frac{\nu_{12}E_2}{E_1} \quad (17.11)$$

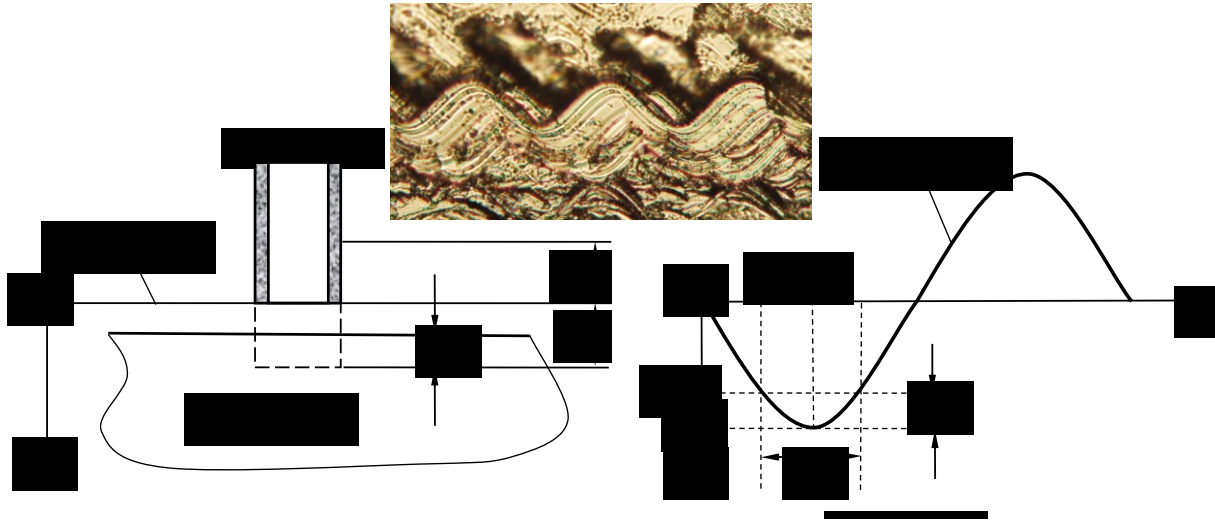
17.2.7 Impulse, impact force, and cutting force

Assuming the abrasive grains are rigid, the impulse in terms of maximum impact force (F_i) during one cycle of ultrasonic vibration

$$\text{Impulse} = \int_{\text{cycle}} F_i dt \approx F_i \Delta t \quad (17.12)$$

where Δt is the time during which an abrasive particle is penetrating into the workpiece (effective contact time), s.

Figure 17.6 Calculation of effective cutting time Δt (after [Pei et al., 1995b]).



In RUM, the cutting tool oscillates up and down and rotates simultaneously. Therefore, an abrasive particle at the end face of tool moves along a sine wave which can be observed from machined surface, as shown in

Figure 17.6. A is the amplitude of ultrasonic vibration. It takes an abrasive particle a time of $t/2$ to move from $z = (A - \delta)$ to $z = A$. Δt can be calculated using the following equation.

$$\Delta t = 2(t_1 - t_2) = \frac{1}{\pi f} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right] \quad (17.13)$$

where f is the frequency of ultrasonic, Hz.

The impulse in terms of the cutting force F during one cycle of ultrasonic vibration

$$\text{Impulse} = \frac{F}{f} \quad (17.14)$$

where,

F is the cutting force measured during the experiments in RUM of CFRP, N;

The cutting force (F) measured during RUM is different from maximum impact force between tool and workpiece (F_i). By equating the two impulse equations (Equation 17.12 and Equation 17.14), the following relationship can be obtained

$$\frac{F}{f} = F_i \Delta t \quad (17.15)$$

Equation 14 can also be expressed as

$$F = \Delta t f F_i = n \Delta t f F_1 \quad (17.16)$$

Substituting Equation 17.4 and Equation 17.13 into Equation 17.16, the following equation can be obtained

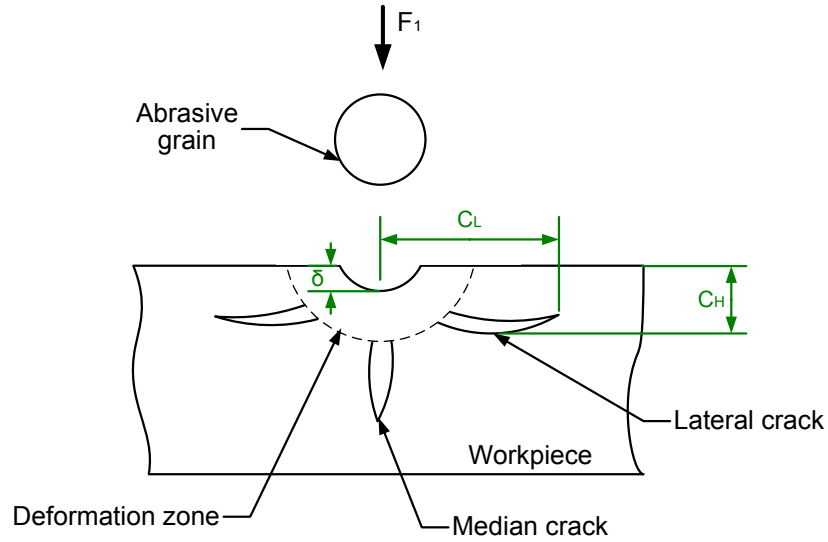
$$F = \Delta t f F_i = \left[\frac{1}{2} - \frac{1}{\pi} \arcsin \left(1 - \frac{\delta}{A} \right) \right] \frac{8^{1/2} n E d^{1/2} \delta^{3/2}}{3(1-\nu^2)} \quad (17.17)$$

17.2.8 Material removal volume by one abrasive particle

Material removal mechanism in RUM of CFRP is mainly attributed to brittle fracture. The brittle fracture mechanism has been discussed using indentation fracture [Lawn and Wilshaw, 1975; Ostojic and Mcpherson, 1987; Lawn et al., 1980; Marshall et al., 1982]. By the indentation of brittle materials, the radial, median, and lateral cracks form and propagate. The

material from the workpiece will be removed if the lateral cracks form due to two adjacent indentations [Komaraiah and Reddy, 1993]. The lateral crack length (C_L) and depth (C_H) are illustrated in Figure 17.7.

Figure 17.7 Cracks in brittle material induced by indentation of an abrasive grain [Lawn et al., 1980].



Abrasive grain on the end face of tool moves along a sine wave. During the period of time Δt , the indentation of the abrasive grain increases from 0 to δ then decreases to 0 due to ultrasonic vibration and abrasive grain slides a distance L on the workpiece surface due to rotation of cutting tool. As a result, the length and width of fracture zone by lateral crack also increase from 0 to their maximum values then decrease to 0. The fracture zone for one grain can be illustrated in Figure 17.8. The fracture zone can be simplified as volume of a half ellipse with three half-axes length of C_L , C_H , and $\frac{L}{2}$. So the volume can be calculated by

$$V_1 = \frac{1}{3} \pi C_L C_H L \quad (17.18)$$

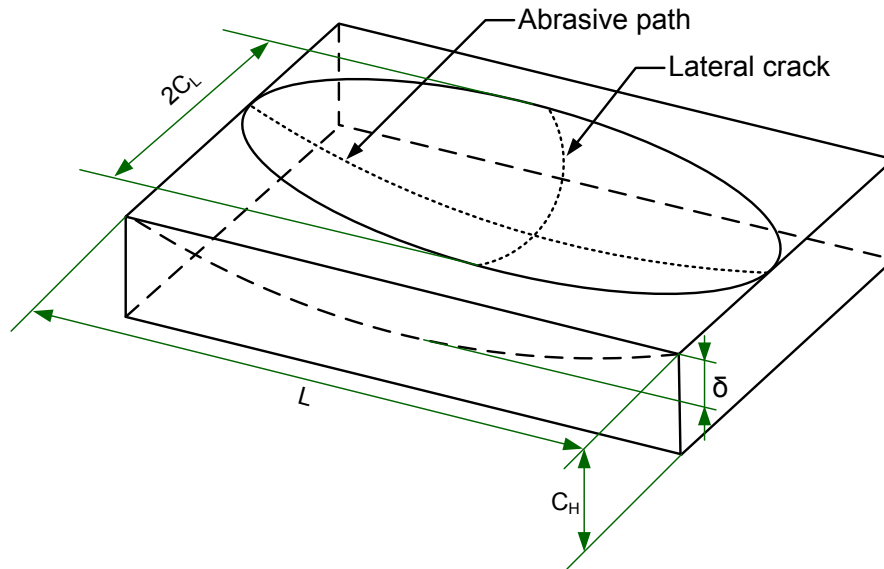
where,

C_L is the lateral crack length, mm;

C_H is the lateral crack depth, mm;

L is the effective cutting distance that an abrasive particle travels during effective cutting time Δt .

Figure 17.8 Theoretical volume of fracture zone.



The effective cutting distance (L) that an abrasive particle travels during effective cutting time (Δt) can be calculated by

$$L = \frac{\pi D S}{60} \Delta t \quad (17.19)$$

where,

S is the tool rotation speed, rpm;

D is the diameter of the cutting tool, mm;

The cutting tool, a core drill with a certain thickness, has outer diameter D_o and inner diameter D_i . D can be calculated by

$$D = \frac{D_o + D_i}{2} \quad (17.20)$$

Substituting Equation 17.13 into Equation 17.19, the following equation can be obtained

$$L = \frac{DS}{60f} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right] \quad (17.21)$$

The lateral crack length (C_L) and lateral crack depth (C_H) are given by [Markov, 1966; Komaraiah and Reddy, 1993]

$$C_L = k_L \left(\frac{F_1}{K_C} \right)^{3/4} \quad (17.22)$$

$$C_H = k_H (d\delta - \delta^2)^{1/2} \quad (17.23)$$

where,

k_L , is lateral crack length factor;

k_H , is lateral crack depth factor;

(k_L or k_H is the constant of proportionality and could be treated as a function of the material properties, process parameters, probability of causing fracture, etc.);

K_C is the fracture toughness expressed in stress intensity factor, $\text{MPa} \cdot \sqrt{\text{mm}}$.

K_C can be calculated by [Matthews et al., 2003]

$$K_c^2 = E_2 G_c \quad (17.24)$$

where G_c is fracture toughness expressed in elastic energy release rate, J/m^2 .

G_c can be calculated by [Matthews et al., 2003]

$$G_c \cong 2(G_{cf}V_f + G_{cm}V_m) \quad (17.25)$$

where G_{cf} and G_{cm} are fracture toughness in elastic energy release rate for fiber and matrix, respectively.

By comparing Equation 17.21 with Equation 17.22, the fracture toughness expressed in stress intensity factor for CFRP can be calculated by

$$K_c \cong [2E_2(G_f v_f + G_m v_m)]^{1/2} \quad (17.26)$$

Substituting Equations 17.21, 17.22, and 17.23 into Equation 17.18, material removal volume by one abrasive particle can be calculated by

$$V_1 = \frac{1}{3} K_v \pi \left(\frac{F_1}{K_C} \right)^{3/4} (d\delta - \delta^2)^{1/2} \left\{ \frac{DS}{60f} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right] \right\} \quad (17.27)$$

where K_v is fracture volume factor ($K_v = k_L \cdot k_H$) which is a proportionality parameter. It is assumed to be constant for a given workpiece material over a wide range of input variables.

17.2.9 Material removal rate

Material removal rate can be theoretically calculated from the summation of material removal rate of all abrasive particles on the end face of the cutting tool. The material removal rate can be calculated by

$$MRR = n f V_1 = K_v \frac{n \pi S}{180} (D_o + D_i) \left(\frac{F_1}{K_C} \right)^{3/4} (d\delta - \delta^2)^{1/2} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right] \quad (17.28)$$

According to the definition of material removal rate, it can also be expressed in term of the feedrate (F_r) and area of the cutting tool end face (A_0)

$$MRR = F_r A_0 = \frac{\pi(D_o^2 - D_i^2)}{4} F_r \quad (17.29)$$

17.2.10 The cutting force model

By equating Equation 17.28 and Equation 17.29, the relationship between F_1 and δ can be obtained

$$\frac{\pi(D_o^2 - D_i^2)}{4} F_r = K_v \frac{n\pi S}{180} (D_o + D_i) \left(\frac{F_1}{K_C} \right)^{3/4} (d\delta - \delta^2)^{1/2} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right] \quad (17.30)$$

From Equation 17.3, we know $F_1 = \frac{8^{1/2} E d^{1/2} \delta^{3/2}}{3(1 - \nu^2)}$.

In the simultaneous equations (Equations 17.3 & 17.30), there are three unknowns including fracture volume factor (K_v), indentation depth (δ), and the calculated maximum impact force for one diamond grain (F_1). K_v is independent factor for a given material over a wide range of input variables. It can be used to develop the equation for MRR and then experimentally investigations are needed to obtain its value.

By substituting the calculated maximum impact force for one diamond grain (F_1) and indentation depth (δ) into Equation 17.16, $F = n \left[\frac{1}{2} - \frac{1}{\pi} \arcsin \left(1 - \frac{\delta}{A} \right) \right] F_1$, the cutting force can be calculated.

From Equations 17.3, 17.4, and 17.30, cutting force model can also be expressed as

$$\left\{ \begin{array}{l} \frac{\pi(D_o^2 - D_i^2)}{4} F_r = K_v \frac{n^{1/4} \pi^2 S}{180} (D_o + D_i) \left(\frac{F}{K_C} \right)^{3/4} (d\delta - \delta^2)^{1/2} \left[\frac{1}{2} - \frac{1}{\pi} \arcsin \left(1 - \frac{\delta}{A} \right) \right]^{1/4} \\ F = \frac{8^{1/2} E d^{1/2} \delta^{3/2}}{3n(1 - \nu^2) \left[\frac{1}{2} - \frac{1}{\pi} \arcsin \left(1 - \frac{\delta}{A} \right) \right]} \end{array} \right. \quad (17.31)$$

17.3 Process of obtaining fracture volume factor (K_V)

17.3.1 Methodology

Simultaneous Equations 17.17 & 17.18 are relationship between between F_1 and δ when cutting force is unknown.

$$\begin{cases} F_1 = \frac{8^{1/2} E d^{1/2} \delta^{3/2}}{3(1-\nu^2)} \\ F = n \left[\frac{1}{2} - \frac{1}{\pi} \arcsin \left(1 - \frac{\delta}{A} \right) \right] F_1 \end{cases} \quad (17.32)$$

F_1 and δ can be calculated by Equation 17.32 once obtained cutting force (F) from experiments and substituted into Equation 17.32. Then the K_V can be calculated.

$$K_V = \frac{MRR}{MRR_1} = \frac{\frac{\pi(D_o^2 - D_i^2)}{4} F_r}{\frac{n\pi S}{180} (D_o + D_i) \left(\frac{F_1}{K_C} \right)^{3/4} (d\delta - \delta^2)^{1/2} \left[\frac{\pi}{2} - \arcsin \left(1 - \frac{\delta}{A} \right) \right]} \quad (17.33)$$

17.3.2 Experimental set-up and conditions

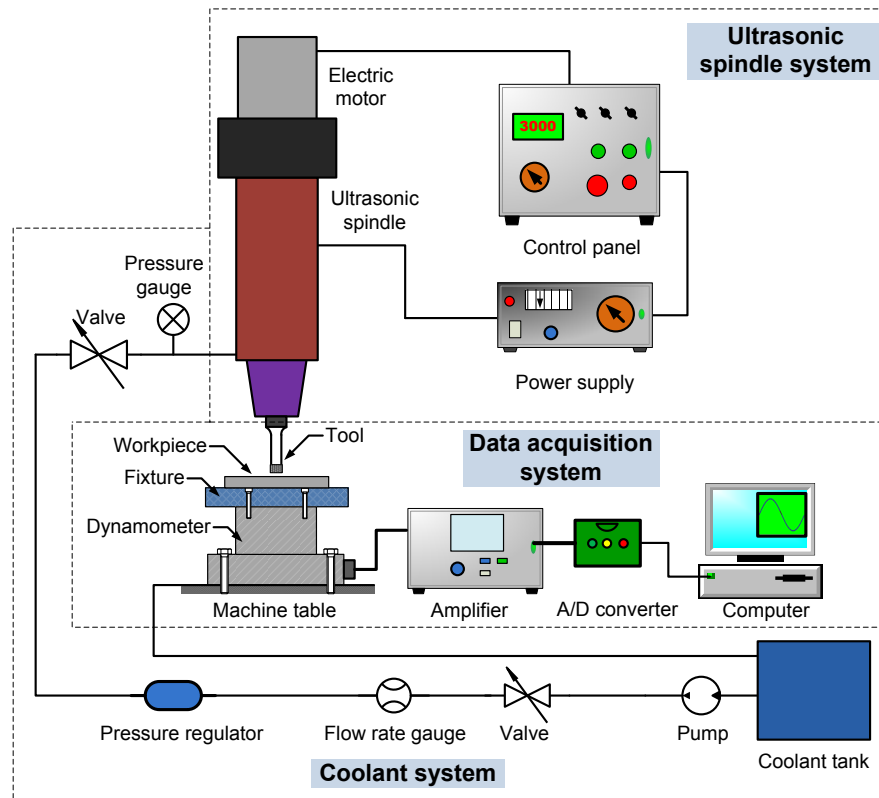
Workpiece properties

The workpiece material was CFRP composite with the dimension of 200 mm × 150 mm × 16 mm. The CFRP was composed of carbon fibers and epoxy resin matrix. Plain woven fabric of carbon fibers had an orientation of 0/90 degrees. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The CFRP contained 21 layers of fabric (42 layers of carbon fiber). The workpiece properties are listed in Table 17.1.

Table 17.1 CFRP workpiece and its component properties.

Property	Unit	Value
Density of CFRP	kg/m ³	1550
Hardness (Rockwell)	HRB	70-75
Density of carbon fiber	kg/m ³	1800
Elastic modulus of carbon fiber	GPa	230
Tensile strength of carbon fiber	GPa	5
Poisson's ratio of carbon fiber	-	0.3
Fracture toughness of carbon (Energy/G _c)	J/m ²	2
Density of epoxy matrix	kg/m ³	1200
Elastic modulus of epoxy matrix	GPa	4.5
Tensile strength of epoxy matrix	MPa	130
Poisson's ratio of epoxy matrix	-	0.4
Fracture toughness of epoxy matrix (Energy/G _c)	J/m ²	500

Figure 17.9 RUM system set-up.



Experimental set-up and cutting force measurement

The experiments were performed on a rotary ultrasonic machine (Series 10, Sonicmill, Albuquerque, NM, USA). The rotary ultrasonic machining set-up mainly consisted of three subsystems, as illustrated in Figure 17.9, including an ultrasonic spindle system, a data acquisition system, and a coolant system. The major components in the ultrasonic spindle system had an ultrasonic spindle, an ultrasonic power supply, an electric motor, a hydraulic feeding device, and a control panel. The power supply converted low frequency electricity to 20 kHz electrical energy. This high-frequency electrical energy was provided to a piezoelectric converter that changed high-frequency electrical energy to high-frequency mechanical vibration (namely ultrasonic vibration). Acoustic horn amplified and transmitted the ultrasonic vibration to the cutting tool. This caused the cutting tool to vibrate at the frequency of 20 kHz. The amplitude of ultrasonic vibration could be adjusted by changing the level of output control of the power supply. The motor atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds could be obtained by adjusting the motor speed controller on the control panel. The data acquisition system included dynamometer, charge amplifier, A/D convertor, and computer with software. A dynamometer (Model 9272, Kistler Inc., Winterthur, Switzerland) was used to measure the cutting force (F_z) in the axial direction. The electrical signals from the dynamometer were amplified by a charge amplifier (Model 5070A, Kistler Inc., Winterthur, Switzerland) and then transformed into digital signals by an A/D converter. After being processed by a signal conditioner, the digital signals were collected by a data acquisition card (PC-CARD-DAS16/16, Measurement Computing Corporation, Norton, MA, USA) on a computer with the help of Dynoware software (Type 2815A, Kistler Inc., Winterthur, Switzerland). The coolant system was comprised of pump, coolant tank, pressure regulator, flow

rate and pressure gauges, and valves. The coolant system provided coolant to the spindle and the interface of machining.

Figure 17.10 Illustration of cutting tool.

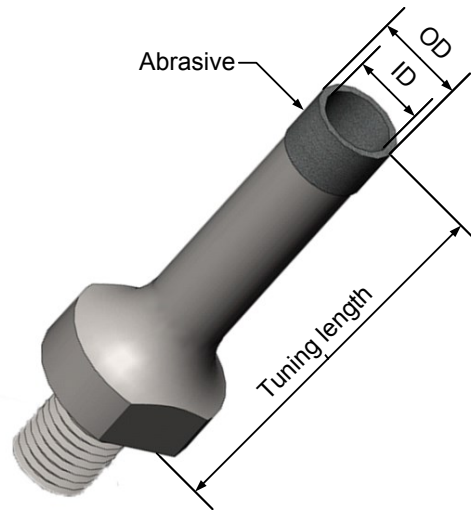


Table 17.2 Identifications of cutting tools in experiments.

Tool #	Mesh size	Abrasive size d (mm)	Concentration C_a	Outer diameter D_o (mm)	Inner diameter D_i (mm)
1	#60-80	0.201	100	9.54	7.82
2	#80-100	0.162	100	9.54	7.82
3	#60-80	0.201	100	12.7	11.05
4	#80-100	0.162	100	12.7	11.05
5	#220	0.07	100	12.7	11.05
6	#300	0.048	100	12.7	11.05
7	#80-100	0.162	100	22.2	20.3
8	#80-100	0.162	100	5	3.2

Cutting tools and tool variables

The cutting tools, as illustrated in Figure 17.10, were metal-bonded diamond core drills (N.B.R. Diamond Tool Corp., LaGrangeville, NY, USA). The major cutting tool variables include outer and inner diameters (OD and ID), abrasive size, and abrasive concentration. Other

tool variables include tuning length (1.5” to 1.75” in this study), bond type (type B in this study), and abrasive type (diamond in this study). The details of cutting tools used in this study were listed in Table 17.2.

Input variables

Considering the limitations of the experimental set-up (for example, vibration frequency was fixed at 20 kHz on the machine), only the following input variables were changed in the experiments:

- Ultrasonic power: Percentage of power from ultrasonic power supply to control the ultrasonic vibration amplitude;
- Tool rotation speed: Rotational speed of cutting tool;
- Feedrate: Feedrate of cutting tool;
- Abrasive size: Diameter of abrasive in the cutting tool;
- Tool outer diameter: Outside diameter of cutting tool.

17.3.3 Design of experiments

If K_V is independent of input variables, theoretically only one experiment is needed to get its value for a given material. However, to verify whether it is indeed independent of input variables, a number of difficult experiments for various combinations of input variables are needed.

The experimental design is shown in Table 17.3. The experiments involved six input variables (ultrasonic vibration amplitude, tool rotation speed, feedrate, abrasive size, tool outer diameter, and abrasive concentration). Note that the cutting tools with the different outer

diameters and the same wall thickness led to different area of the cutting tool end face and different numbers of active abrasive grains on the end face. Different cutting tools led to different amplitude under the same ultrasonic power. The ultrasonic vibration amplitude during RUM process was measured using the method reported by Cong et al. [2011c].

Table 17.3 Experimental conditions for obtaining K_V .

Experiment #	Vibration amplitude A (mm)	Tool rotation speed S (rpm)	Feedrate F_r (mm/s)	Tool #
No. 1	0.0035; 0.0135; 0.0225; 0.03	3000	0.5	No. 2
No. 2	0.0135	1000; 2000; 3000; 4000; 5000	0.5	No. 2
No. 3	0.0135	3000	0.1; 0.3; 0.5; 0.7; 0.9	No. 2
No. 4	0.01	3000	0.3	No. 3; 4; 5; 6
No. 5	0.0135 for #2 0.01 for #4 0.011 for #7 0.005 for #8	3000	0.3	No. 2; 4; 7; 8

17.3.4 Analysis of K_V from experimental results

According to the experimental results, the cutting force applied on one abrasive grain F_1 and indentation depth δ can be obtained. Then MRR_1 (summation of material removal rate of all abrasive particles on the cutting tool end face with K_V equal to 1) and MRR (material removal rate calculated by feedrate and tool end face area) in Equation 17.32 can be calculated. The relationships between MRR_1 and MRR are plotted in Figure 17.11. The experimental data can be well fitted to a regression line, and the R^2 value of this regression line is 96%, indicating 96% of the variation in MRR can be explained by the linear relationship between MRR and MRR_1 . The

slope of the regression line passing through the origin is the factor K_V . It can be seen that the K_V for all these experimental results on RUM of CFRP is 0.0022.

Figure 17.11 Calculation of K_V from experimental results.

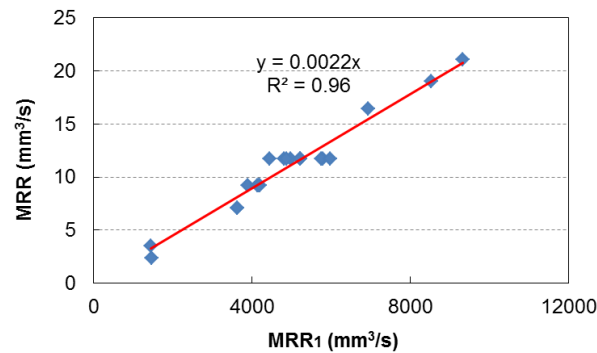
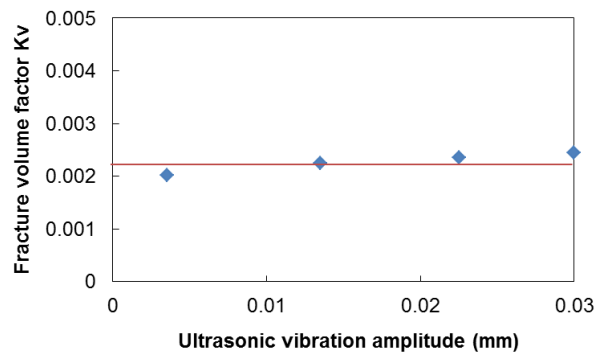


Figure 17.12 illustrates effects of input variable (ultrasonic vibration amplitude, tool rotation speed, feedrate, abrasive size, and tool outside diameter) on fracture volume factor (K_V). It can be seen that these input variables have little effects on K_V . The assumption of K_V being constant for a particular material is reasonable, although there are some deviations of K_V among the data. K_V for a given material is a specific value and can estimate the cutting force under different input variables.

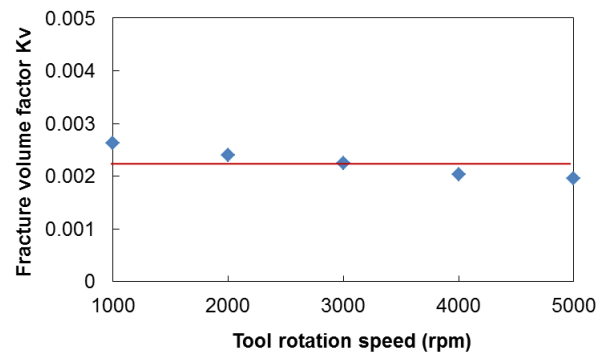
17.4 Predicted influences of input variables on cutting force

Base on this cutting force mechanistic model in RUM of CFRP, the effects of input variables on cutting force can be predicted. The properties of the workpiece used in this prediction listed in Table 17.1. The K_V is taken as 0.0022. The outer diameter, inner diameter, and tuning length of cutting tool used in this prediction are 9.54 mm, 7.82 mm, and 45 mm, respectively.

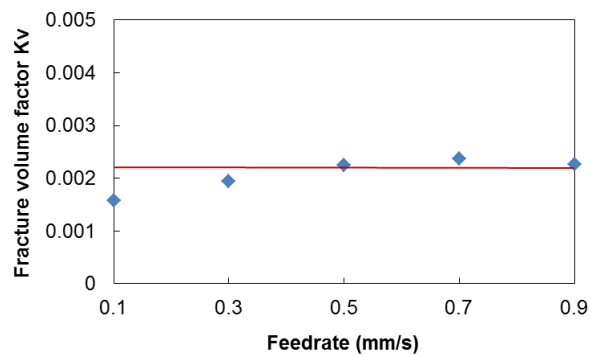
Figure 17.12 Influence of input variables on K_v .



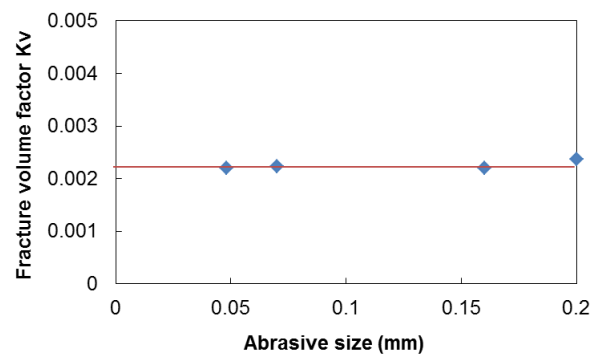
(a) Effects of ultrasonic vibration amplitude



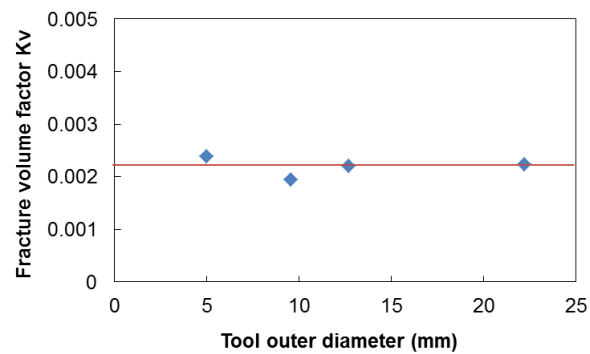
(b) Effects of tool rotation speed



(c) Effects of feedrate



(d) Effects of abrasive size



(e) Effects of tool outside diameter

17.4.1 Predicted results on cutting force

The predicted results on cutting force under different input variables, including ultrasonic vibration amplitude, tool rotation speed, feedrate, abrasive size, and tool outside diameter, are plotted in Figure 17.13. It can be seen that cutting force decreases remarkably as feedrate decreases, tool rotation speed increases, or abrasive size increases. Cutting force decreases slightly with increase of ultrasonic vibration amplitude or decrease of abrasive concentration. With increasing of tool rotation speed, feedrate, and abrasive size increase cutting force changes remarkably, while, with increasing of ultrasonic vibration amplitude and abrasive concentration cutting force changes slightly. The relationship between cutting force and feedrate under different levels of tool rotation speed is linear. However, the relationship between cutting force and other input variables are nonlinear.

17.4.2 Predicted results on important intermediate variables

To explain the predicted relationships between input variables (ultrasonic vibration amplitude, tool rotation speed, feedrate, abrasive size, and abrasive concentration) and cutting force, the influences of these input variables on intermediate variables have been studied. These intermediate variables, for individual diamond grain, include indentation depth δ , effective contact time Δt , and maximum impact force F_1 .

Figure 17.13 Predicted results on cutting force under different input variables.

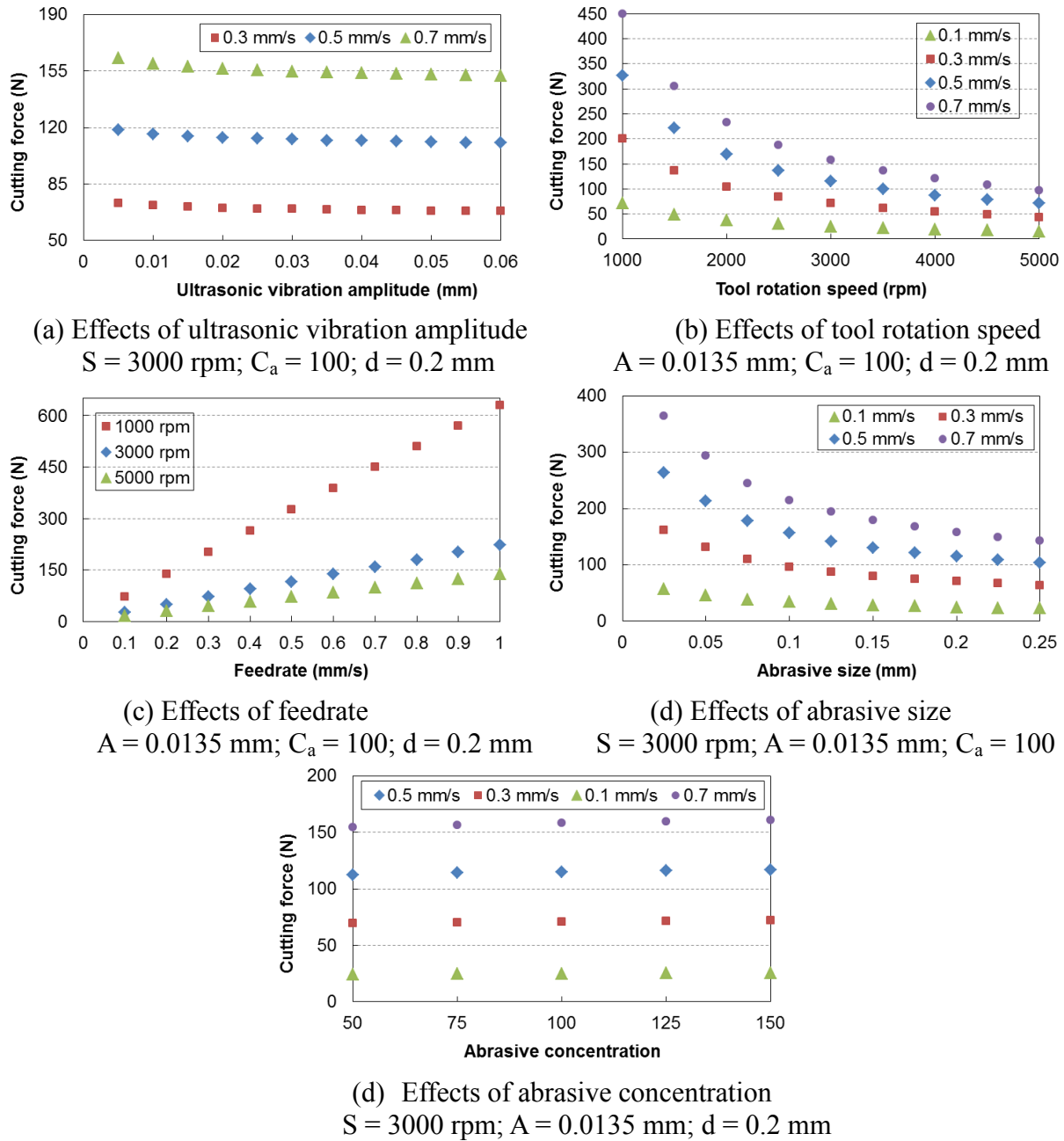
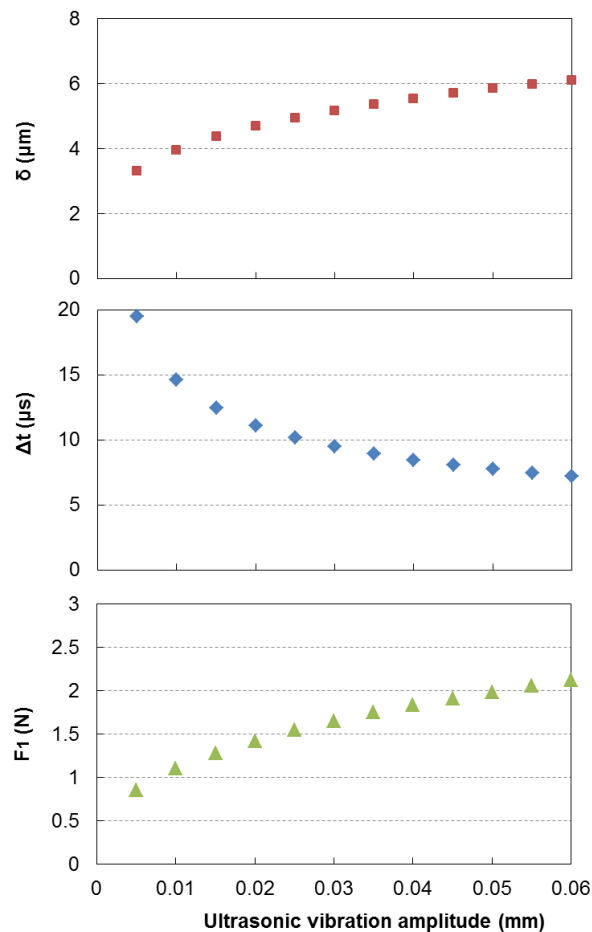


Figure 17.14 shows influences of ultrasonic vibration amplitude on intermediate variables. With increase of ultrasonic vibration amplitude A , indentation depth δ increases. Increase in indentation depth δ results in increase in max impact force F_1 increases. There is no linear relationship between ultrasonic vibration amplitude A and indentation depth δ and the ratio of

δ/A is the slope of the δ - A curve. With increase of ultrasonic vibration amplitude A , the ratio of δ/A decreases. Decrease in δ/A leads to decrease in effective cutting time Δt . However, increasing rate of max impact force F_1 is lower than decreasing rate of effective cutting time Δt . Based on Equation 17.16, $F = \Delta t f F_i = n \Delta t f F_1$, if ultrasonic vibration amplitude A increases and number of active abrasive grains n and ultrasonic frequency f keep unchanged, cutting force F will decrease.

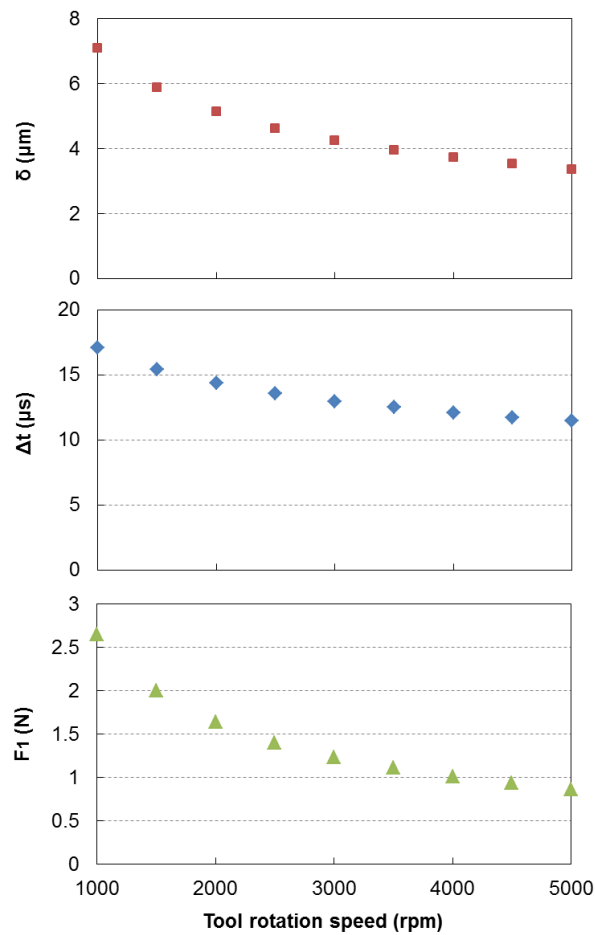
Figure 17.14 Influences of ultrasonic vibration amplitude.



$S = 3000 \text{ rpm}$; $F_r = 0.5 \text{ mm/s}$; $C_a = 100$; $d = 0.2 \text{ mm}$

Figure 17.15 shows influences of tool rotation speed on intermediate variables. If feedrate F_r does not change, MRR (as well as on abrasive grain material removed volume V_1) will not change. Increase in tool rotation speed results in increase of effective cutting distance L . To keep the material removed volume V_1 unchanged, the indentation depth δ needs to decrease. In this case, effective cutting time Δt and max impact force F_1 decrease accordingly. Based on Equation 17.16, $F = \Delta t f F_i = n \Delta t f F_1$, if tool rotation speed S increases and number of active abrasive grains n and ultrasonic frequency f keeps unchanged, cutting force F will decrease.

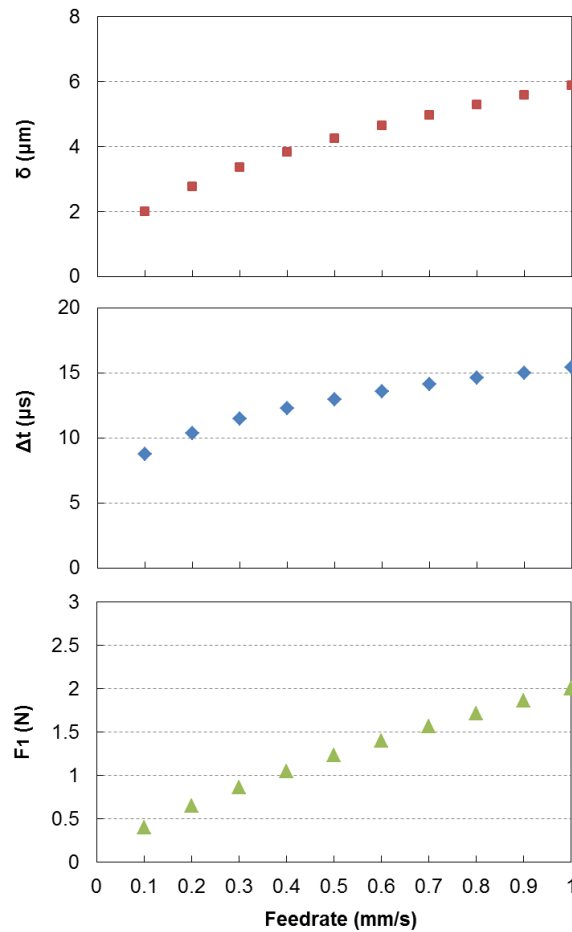
Figure 17.15 Influences of tool rotation speed.



$A = 0.0135 \text{ mm}$; $F_r = 0.5 \text{ mm/s}$; $C_a = 100$; $d = 0.2 \text{ mm}$

Figure 17.16 shows influences of feedrate on intermediate variables. Increase in feedrate F_r leads to increase in MRR (as well as on abrasive grain material removed volume V_1). Indentation depth δ should increase with increase of material removed volume V_1 . Increase in indentation depth δ leads to increase in effective cutting time Δt and max impact force F_1 . From on Equation 17.16, $F = \Delta t f F_i = n \Delta t f F_1$, if feedrate F_r increases and number of active abrasive grains n and ultrasonic frequency f keeps unchanged, cutting force F will increase.

Figure 17.16 Influences of feedrate.

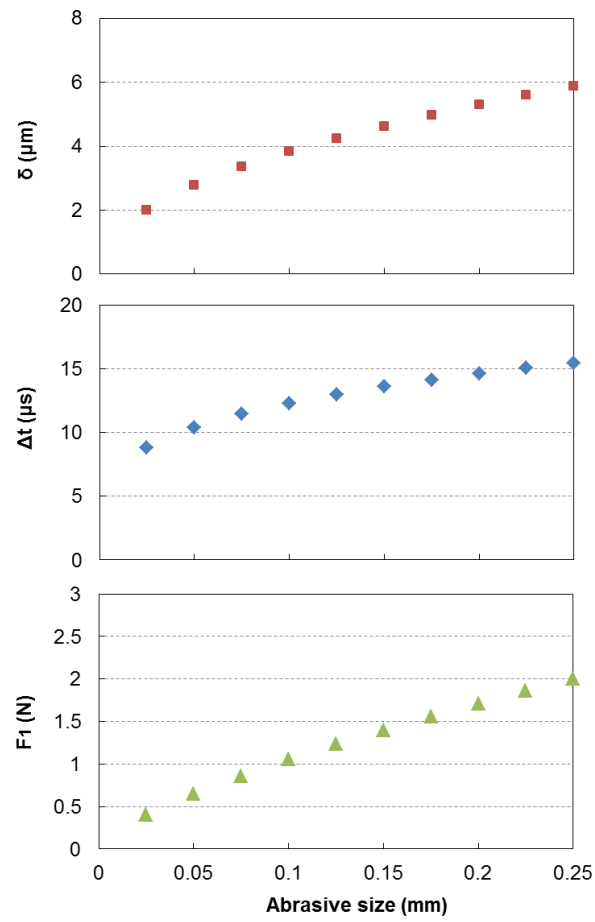


$A = 0.0135 \text{ mm}$; $S = 3000 \text{ rpm}$; $C_a = 100$; $d = 0.2 \text{ mm}$

Figure 17.17 shows influences of abrasive size on intermediate variables. If abrasive size d increases, number of active abrasive grains n decreases. Since feedrate F_r does not change, MRR will not change. In Equation 17.28, $MRR = \eta f V_1$, V_1 should increase to keep MRR unchanged. Indentation depth δ should increase for this reason. Increase in indentation depth δ leads to increase in effective cutting time Δt and max impact force F_1 . The decreasing rate in number of active abrasive grains n caused by increase of abrasive size d is higher than increasing rate in effective cutting time Δt and max impact force F_1 . From on Equation 17.16, $F = \Delta t f F_i = n \Delta t f F_1$, if abrasive size d increases and ultrasonic frequency f keeps unchanged, cutting force F will decrease.

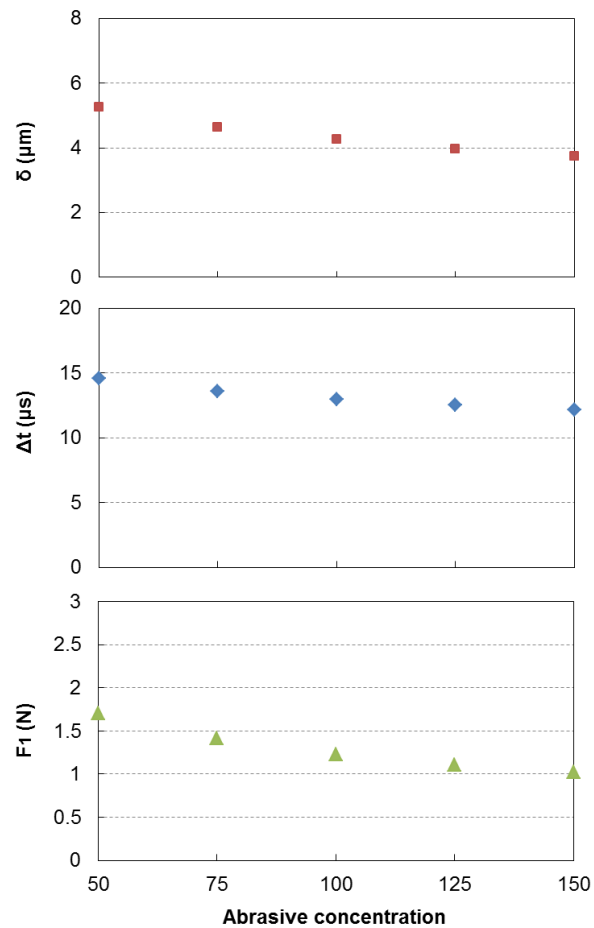
Figure 17.18 shows influences of abrasive concentration on intermediate variables. If abrasive concentration C increases, number of active abrasive grains n increases. Since feedrate F_r does not change, MRR will not change. In Equation 17.28, $MRR = \eta f V_1$, V_1 should decrease to keep MRR unchanged. Indentation depth δ should decrease with decrease of material removed volume V_1 . Effective cutting time Δt and max impact force F_1 decreases when indentation depth δ decreases. The increase rate in number of active abrasive grains n caused by increase of abrasive concentration C is lower than decreased rate in effective cutting time Δt and max impact force F_1 . In Equation 17.16, $F = \Delta t f F_i = n \Delta t f F_1$, if abrasive size d increases and ultrasonic frequency f keeps unchanged, cutting force F will decrease.

Figure 17.17 Influences of abrasive size.



$A = 0.0135 \text{ mm}$; $S = 3000 \text{ rpm}$; $F_r = 0.5 \text{ mm/s}$; $C_a = 100$

Figure 17.18 Influences of abrasive concentration.



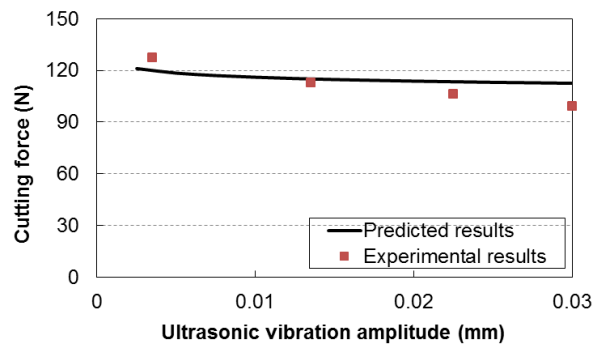
$A = 0.0135$ mm; $S = 3000$ rpm; $F_r = 0.5$ mm/s; $d = 0.2$ mm

17.5 Pilot experimental verification

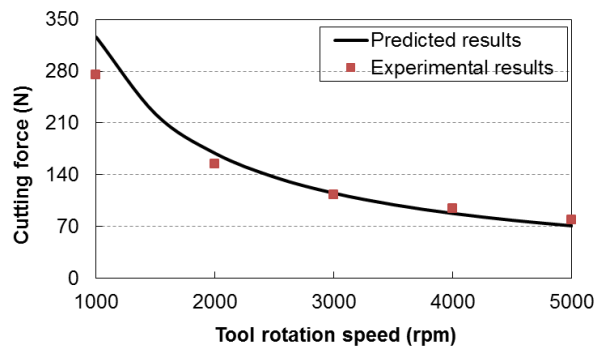
To verify this mechanistic model, a group of experiments were conducted to test effects of input variables (ultrasonic vibration amplitude, tool rotation speed, and feedrate) on cutting force. Only one tool was used to keep the tool variables are the same. The experimental conditions are listed in Table 17.4. A total of ten experiments were conducted by varying each machining variable and keeping other variables the same. The comparisons of predicted and experimental results are shown in Figure 17.19. It can be seen that the trends of predicted results

on effects of input variables (ultrasonic vibration amplitude, tool rotation speed, and feedrate) on cutting force agree well with the trends of experimental results.

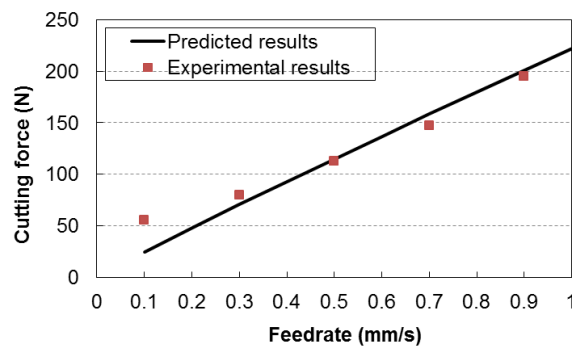
Figure 17.19 Comparisons of predicted and experimental results.



(a) Effects of ultrasonic vibration amplitude
 $S = 3000$ rpm; $F_r = 0.5$ mm/s; $C_a = 100$; $d = 0.2$ mm



(b) Effects of tool rotation speed
 $A = 0.0135$ mm; $F_r = 0.5$ mm/s; $C_a = 100$; $d = 0.2$ mm



(e) Effects of feedrate
 $S = 3000$ rpm; $A = 0.0135$ mm; $C_a = 100$; $d = 0.2$ mm

Table 17.4 Experimental conditions for model verification.

Input variable	Unit	Value
Tool rotation speed, S	rpm	1000; 2000; 3000; 4000; 5000
Feedrate, F_r	mm/s	0.1; 0.3; 0.5; 0.7; 0.9
Ultrasonic power (ultrasonic vibration amplitude), A	% (mm)	20% (0.0035); 40% (0.0135); 60% (0.0225); 80% (0.03)
Cutting tool	Tool #	No. 1

17.6 Conclusions

A mechanistic model to predict cutting force for RUM of CFRP has been developed. CFRP material removal mechanism has been analyzed. The model is based on the assumption that brittle fracture is the dominant mode of material removal. CFRP micromechanical analysis has been conducted to represent CFRP as an equivalent homogeneous material.

Experimental investigations were conducted to estimate the fracture volume factor K_V and verify that it is constant over the entire range of machining variables and tool variables. Analysis of the experimental data indicated that it is reasonable to assume the parameter is constant.

This model is the first cutting force model for RUM of CFRP composites. The model has been used to study the influences of different input variables on cutting force. The effects on intermediate variables for single individual abrasive grain have been investigated using this model to explain predicted relationships by the cutting force model. The trends predicted by the model are consistent with those of experimental results. The predicted trends are as follows. Cutting force decreases with decrease of feedrate and abrasive concentration and increase of ultrasonic amplitude, tool rotation speed, and abrasive size.

Cutting force is related to cutting temperature, tool wear, surface roughness, and workpiece delamination in RUM of CFRP composites. The cutting force model can help to build the models to predict these output variables.

Acknowledgements

The work was supported by National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to Mr. Clyde Treadwell in Sonic-Mill Corporation and Mr. Timothy Deines in Kansas State University for technical support.

References

- [1] [Arul et al., 2006] Arul, S., Vijayaraghavan, L., Malhotra, S.K., and Krishnamurthy, R., 2006, The effect of vibratory drilling on hole quality in polymeric composites, International Journal of Machine Tools and Manufacture, 46(3-4), pp. 252-259.
- [2] [Barbero, 2010] Barbero, E.J., 2010, Chapter 4 Micromechanics, Introduction to Composite Material Design, 2nd ed., CRC Press, Taylor & Francis Group, LLC., Boca Raton, FL, USA.
- [3] [Boeing website] 787 Dreamliner Program Fact Sheet, <http://www.boeing.com/commercial/787family/programfacts.html>
- [4] [Chung, 2010] Chung, D.D.L., 2010, Composite Materials Science and Applications, Second edition, Springer-Verlag London Ltd., London, UK.
- [5] [Cong 2011a] Cong, W.L., Feng, Q., Deines, T., Pei, Z.J., and Treadwell, C., 2011, Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables, Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference, Corvallis, OR, USA, June 13-17.

- [6] [Cong et al., 2011b] Cong, W.L., Pei, Z.J., Deines, T.W., and Treadwell, C., 2011, Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions, *Journal of Reinforced Plastics and Composites*, 30(10), pp. 899-906.
- [7] [Cong et al., 2011c] Cong, W.L., Pei, Z.J., Mohanty, N., Van Vleet, E., and Treadwell, C., 2011, Vibration amplitude in rotary ultrasonic machining: a novel measurement method and effects of process variables, *Journal of Manufacturing Science and Engineering*, 133(3), pp. 034501-1– 034501-6.
- [8] [Cong et al., 2012a] Cong, W.L., Pei, Z.J., Feng, Q., Deines, T.W., and Treadwell, C., 2012, Rotary ultrasonic machining of CFRP: a comparison with twist drilling, *Journal of Reinforced Plastics and Composite*, 31(5), pp. 313-321.
- [9] [Cong et al., 2012b] Cong, W.L., Pei, Z.J., Feng, Q., Deines, T.W., and Treadwell, C., Rotary ultrasonic machining of carbon fiber reinforced plastic composites: using cutting fluid versus cold air as coolant, *Journal of Composite Materials*, DOI: 10.1177/0021998311424625.
- [10] [Cong et al., 2012c] Cong, W.L., Pei, Z.J., Deines, T.W., Srivastava, A., Riley, L., and Treadwell, C., 2012, Rotary ultrasonic machining of CFRP composites: a study on power consumption, *Ultrasonics*, <http://dx.doi.org/10.1016/j.bbr.2011.03.031>.
- [11] [Davim and Reis, 2003] Davim, J.P., and Reis, P., 2003, Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, *Materials and Design*, 24(5), pp. 315-324.
- [12] [Denkena et al., 2008] Denkena, B., Boehnke, D., Dege, J.H., 2008, Helical milling of CFRP-titanium layer compounds, *CIRP Journal of manufacturing Science and Technology*, 1(2), pp. 64-69.

- [13] [Dharan, 1978] Dharan C.K.N., 1978, Fracture Mechanics of Composite Materials, Journal of Engineering Materials and Technology, 100(233), pp. 233-247.
- [14] [Enemuoh 2001] Enemuoh, E.U., El-Gizawy A.S., and Okafor, A.C., 2001, An approach for development of damage-free drilling of carbon fiber reinforced thermosets, International Journal of Machine Tools and Manufacture, 41(12), pp. 1795-1814
- [15] [Feng et al., 2012] Feng, Q., Cong, W.L., Pei, Z.J., and Ren, C.Z., 2012, Rotary ultrasonic machining of carbon fiber reinforced polymer: feasibility study, Machining Science and Technology, 16(3), pp. 380-398.
- [16] [Gaitonde et al., 2007] Gaitonde, V.N., Karnik, S.R., Campos Rubio, J., Esteves Correia, A., Abrão, A.M., and Paulo Davim, J., 2007, Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites, Journal of Materials Processing Technology, 203(1-3), pp. 431-438.
- [17] [Garrrick, 2007] Garrick, R., 2007, Drilling advanced aircraft structures with PCD (Poly-Crystalline Diamond) Drills, AeroTech Congress & Exhibition, September 2007, Los Angeles, CA, USA.
- [18] [Gay et al., 2003] Gay, D., Hoa, S.V., and Tsai, S.V., 2003, Composite Materials Design and Applications, 4th ed., CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida, USA.
- [19] [Guu et al., 2001] Guu, Y.H., Hocheng, H., Tai, N.H., and Liu, S.Y., 2001, Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, Journal of Materials Science, 36(8), pp. 2037-2043.

- [20] [Hocheng and Dharan, 1990] Hocheng H., and Dharan CKH, 1990, Delamination during drilling in composite laminates, *Journal of Engineering for Industry (Transactions of the ASME)*, 112(3), pp. 236-239.
- [21] [Hocheng and Tsao, 2005] H. Hocheng , C.C. Tsao, 2005, The path towards delamination-free drilling of composite materials, *Journal of Materials Processing Technology*, 167(2-3), pp. 251-264.
- [22] [Hocheng and Tsao] Hocheng, H., and Tsao, C.C., 2006, Effects of special drill bits on drilling-induced delamination of composite materials, *International Journal of Machine Tools and Manufacturing*, 46(12-13), pp. 1403-1416.
- [23] [Kaw, 2006] Kaw A.K., 2006, Chapter 3 Micromechanical analysis of a lamina, *Mechanics of Composite Materials*, 2nd ed., CRC Press, Taylor & Francis Group, LLC., Boca Raton, FL, USA.
- [24] [Komaraiah and Reddy, 1993] Komaraiah, M., and Reddy, P.N., 1993, A study on the influence of workpiece properties in ultrasonic machining, *International Journal of Machine Tools & Manufacture*, 33(3), pp. 495-505.
- [25] [Lambert, 1987] Lambert, B.K., 1987, Cutting and drilling of composite materials, *The Carbide and Tool Journal*, 19(5), pp. 31-34.
- [26] [Lawn and Wilshaw, 1975] B. Lawn, R. Wilshaw, Review indentation fracture: principles and applications, *Journal of Materials Science*, 10(6), pp. 1049-1081.
- [27] [Lawn et al., 1980] Lawn, B.R., Evans, A.G., Marshall, D.B., 1980, Elastic/plastic indentation damage in ceramics: The median/radial crack system, *Journal of the American Ceramic Society*, 63(9-10), pp. 574-581.

- [28] [Lazar, 2012] Lazar M.B., 2012, Cutting Force Modeling for Drilling of Fiber Reinforced Composites, Ph.D. dissertation, Swiss Federal Institutes of Technology in Lausanne, Switzerland.
- [29] [Li et al., 2007] Li, Z.C., Pei, Z.J., Sisco, T., Micale, A.C. and Treadwell, C., 2007, Experimental study on rotary ultrasonic machining of graphite/epoxy panel, Proceedings of the ASPE 2007 Spring Topical Meeting on Vibration Assisted Machining Technology, Chapel Hill, NC, USA.
- [30] [Liu et al., 2012] Liu, D.F., Cong, W.L., Pei, Z.J., and Tang, Y.J., 2012, A cutting force model for rotary ultrasonic machining of brittle materials, International Journal of Machine Tools and Manufacture, 52(1), pp. 77-84.
- [31] [Mallick, 1997] Mallick, P.K., 1997, Composite Engineering Handbook, Marcel Dekker Inc., New York, NY, USA.
- [32] [Markov, 1966] I.A. Markov, Machining of Intractable Materials with Ultrasonic and Sonic Vibrations, Illife Books, 1966.
- [33] [Marshall et al., 1982] D.B. Marshall, B.R. Lawn, A.G. Evans, 1982, Elastic/plastic indentation damage in ceramics: The lateral crack system, Journal of the American Ceramic Society, 65(11), pp. 561-566.
- [34] [Matthews et al., 2003] Matthews, F.L., Davies, G.A.O., Hitchings D., and Soutis, C., 2003, Finite Element Modeling of Composite Materials and Structures, Published in North America by CRC Press LLC, Boca Raton, FL, USA
- [35] [Morgan, P., 2005] Morgan, P., 2005, Carbon Fibers and their composites, CRC Press, Taylor & Francis Group, Boca Raton, FL, USA.

- [36] [Ostojic and Mcpherson, 1987] Ostojic, P., Mcpherson, R., 1987, A review of indentation of fracture: its development, principles and limitations, *International Journal of Fracture*, 33(4), pp. 297-312.
- [37] [Park et al., 1995] Park, K.Y., Choi, J.H., and Lee, D.G., 1995, Delamination-free and high efficiency drilling of carbon fiber reinforced plastics, *Journal of Composite Materials*, 29(15), pp. 1988-2002.
- [38] [Pei and Ferreira, 1998] Pei, Z.J., and Ferreira, P.M., 1998, Modeling of ductile mode material removal in rotary ultrasonic machining, *International Journal of Machine Tools and Manufacture*, Vol. 38, No. 10–11, pp. 1399–1418.
- [39] [Pei et al., 1995a] Pei Z.J., Ferrerra P.M., and Haselkorn M., 1995a, Plastic flow in rotary ultrasonic machining of ceramics, *Journal of Materials Processing Technology*, 48(1-4), pp.771-777.
- [40] [Pei et al., 1995b] Pei, Z.J., Prabhakar, D., Ferreira, P.M., and Haselkorn, M., 1995, A mechanistic approach to the prediction of material removal rates in rotary ultrasonic machining, *Journal of Engineering for Industry*, 117(2), pp. 142-151.
- [41] [Qin et al., 2009] Qin, N., Pei, Z.J., Treadwell, C., and Guo, D.M., 2009, Physics-based predictive cutting force model in ultrasonic-vibration-assisted grinding for titanium drilling, *Journal of Manufacturing Science and Engineering*, 131(4), pp. 041011-1–041011-9.
- [42] [Qin et al., 2011] Qin, N., Pei, Z.J., Cong, W.L., Treadwell, C., and Guo, D.M., 2011, Ultrasonic vibration-assisted grinding of brittle materials: a mechanistic model for cutting force,” *Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference (MSEC)*, Corvallis, OR, June 13-17.

- [43] [Ruegg, C.H., and Habermeier] Ruegg, C.H., and Habermeier, J., 1981, Composite propeller shafts: design and optimization, *Automotive Engineer*, 6(3), pp. 13-15.
- [44] [Sadat, 1995] Sadat, A.B., 1995, Delamination and other types of damage of graphite/epoxy composite caused by machining, *American Society of Mechanical Engineers, Applied Mechanics Division*, 208, pp. 41-52.
- [45] [Schwartz, 1992] Schwartz, M.M., 1992, *Composite Materials Handbook*, Second edition, McGraw-Hill, Columbus, OH, USA.
- [46] [Timoshenko and Goodier, 1970] S. Timoshenko, Goodier, J.N., 1970, *Theory of Elasticity*, third ed., McGraw-Hill, New York, NY, USA
- [47] [Tong et al., 2002] Tong, L., Mouritz A.P., and Bannister M.K., 2002, *3D Fibre Reinforced Polymer Composites*, Elsevier Science Ltd, Oxford, UK.
- [48] [Tsao and Chiu, 2011] Tsao, C.C., and Chiu Y.C., (2011) Evaluation of drilling parameters on thrust force in drilling carbon fiber reinforced plastic (CFRP) composite laminates using compound core-special drills, *International Journal of Machine Tools and Manufacture*, 51(9), pp. 740-744.
- [49] [Tsao and Hocheng, 2005] Tsao, C.C., and Hocheng, H., 2005, Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials, *International Journal of Machine Tools and Manufacture*, 45(2), pp. 125-130.
- [50] [Tsao, 2006] Tsao C.C., 2006, The effect of pilot hole on delamination when core drill drilling composites materials, *International Journal of Machine Tools and Manufacturing*, 46(12-13), pp. 1653-1661.

Chapter 18 - CFRP/Ti Stacks - Feasibility Study

Paper title:

Rotary ultrasonic machining of CFRP/Ti stacks: a feasibility study

Submitted to:

Journal of Manufacturing Science and Engineering

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Deines, T.W.¹, Liu, D.F.² and Treadwell C.³

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
2. College of Mechanical and Electrical Engineering, Central South University, Changsha, Hunan 410083, China
3. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Reported drilling methods for carbon fiber reinforced plastic composite / titanium alloy (CFRP/Ti) stacks include twist drilling, end milling, core grinding, and their derivative methods. The literature does not have any report on drilling of CFRP/Ti stacks using rotary ultrasonic machining (RUM). This paper, for the first time, reports a study on drilling of CFRP/Ti stacks using RUM. It also compares results on drilling of CFRP/Ti stacks using RUM with reported results on drilling of CFRP/Ti stacks using other methods. When drilling CFRP/Ti stacks using RUM, cutting force, torque, and CFRP surface roughness were lower, hole size variation was smaller, CFRP groove depth was smaller, tool life was longer, and there was no obvious Ti exit burr and CFRP entrance delamination. Ti surface roughness when drilling of CFRP/Ti stacks using RUM was about the same as that when using other methods.

Keywords: CFRP composite, Drilling, Grinding, Rotary ultrasonic machining, Stack, Titanium.

18.1 Introduction

Due to the increase of fuel price and market competition, commercial aircraft needs to be lighter and manufactured more efficiently. A recent trend in the aircraft industry is to increase the use of composite materials [Ramulu et al., 2001; Kanirura, 2005]. In the new generation of aircraft, such as Boeing 787, 50% of the total weight was composites [Garrick, 2007; Boeing web; Kanirura, 2005].

In aircraft structure, CFRP composites were often used by stacking up with titanium (Ti) to form stacks [Kim et al., 2005]. Bolting and riveting are currently the preferred methods for fastening CFRP and Ti together in the aircraft assembly [Bennett, 1985, Ramulu et al., 2001; Kim and Ramulu, 2004; Ramulu et al., 2001; Massarweh et al, 1992; Shyha 2010; Lambert, 1979;

Colligan, 1994; Denkena et al., 2008; Brinksmerier et al., 2007]. As a result, a large number of holes need to be drilled in CFRP/Ti stacks [Shyha 2010; Boeing web, Zitoune et al., 2010].

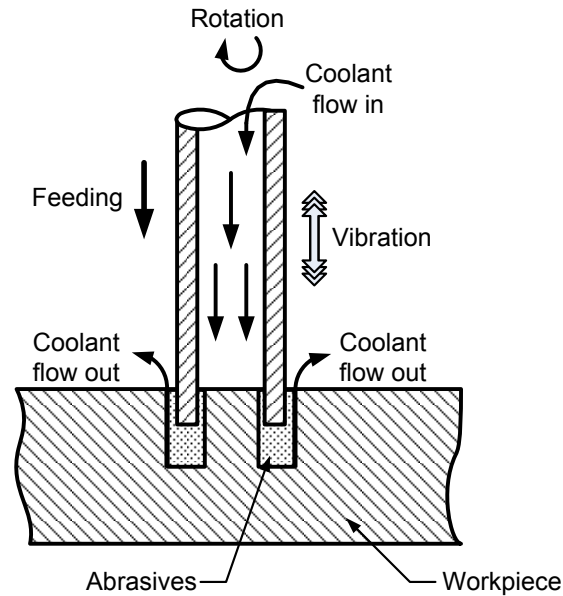
Reported drilling methods for CFRP/Ti stacks include twist drilling, end milling, core grinding, and their derivative methods [Colligan, 1994; Denkena et al., 2008; Yagishita, 2008; Brinksmeier and Janssen, 2002; Garrick, 2007; Shyha et al., 2010; Kim et al., 2001; Ramulu et al., 2001; Kim and Ramulu, 2004, 2005, 2007; Kim et al.; 2005; Yagishita, 2008]. Using these methods, CFRP and Ti were usually drilled with different tools (of different geometries and materials) and different speeds and feedrates [Colligan, 1994]. For example, a three-step method was used in the Boeing Company: (1) Drilling CFRP with a diamond coated twist drill; (2) Drilling Ti with a carbide drill; (3) Reaming the hole with a carbide reamer [Colligan, 1994]. Diamond coated twist drills performed well in CFRP drilling, but they would not last long in Ti drilling, since a lot of heat generated in Ti drilling would degrade the diamond coating on the twist drills. Carbide twist drills performed well in Ti drilling but were worn out very fast in CFRP drilling [Margolis, 2006].

Shortcomings of these methods include high cutting force [Ramulu et al., 2001; Kim and Ramulu, 2005; Yagishita 2008; Shyha et al., 2010], large Ti burr [Kim et al., 2001; Ramulu et al., 2001; Kim and Ramulu, 2004; Kim and Ramulu, 2004; Kim and Ramulu, 2005; Kim et al., 2005 2007; Garrick 2007], groove in composite (the CFRP material near the interface between CFRP and Ti was overcut and a groove was formed) [Brinksmeier and Janssen, 2002; Yagishita 2008], composite delamination [Kim et al., 2001; Kim and Lee, 2005; Kim and Ramulu, 2005; Garrick 2007; Yagishita 2008; Shyha et al., 2010], large variation in hole size [Weiss, 1989; Kim et al., 2001; Garrick 2007], poor surface roughness [Kim et al., 2001; Ramulu et al., 2001; Kim and Ramulu, 2004; Shyha et al., 2010], long cycle time [Colligan 1994], high tool wear rate [Lambert,

1987; Ramulu et al., 2001; Brinksmeier and Janssen, 2002; Kim and Ramulu, 2004; Garrick 2007; Shyha et al., 2010], high cutting temperature [Weiss, 1989; Kim et al., 2001; Ramulu et al., 2001; Kim and Ramulu, 2004], clogging of drill flutes of twist drills [Weiss, 1989; Shyha et al., 2010], and residual stress in Ti [Zitouni et al. 2010]. Therefore, it is desirable to investigate alternative methods in drilling of CFRP/Ti stacks that can reduce or eliminate these shortcomings.

Rotary ultrasonic machining (RUM) is a nontraditional drilling method. Figure 18.1 illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrates axially at an ultrasonic frequency and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf and prevents the tool from jamming and overheating. RUM has been successfully used in drilling of Ti [Churi et al. 2005, 2006, 2007ab; Cong et al., 2011_Ti] and CFRP [Li et al. 2007; Cong et al, 2011, 2012ab] with low cutting force and surface roughness, long tool life, and negligible Ti burr and CFRP delamination. However, there are no reported studies on drilling of CFRP/Ti stacks using RUM.

Figure 18.1 Illustration of rotary ultrasonic machining (RUM).



This paper reports a study on RUM of CFRP/Ti stacks. The results are also compared what with reported results on drilling of CFRP/Ti stacks using other methods. There are four sections in this paper. Following this introduction section, Section 18.2 describes properties and size of CFRP/Ti stacks, experimental set-up and conditions, and measurement procedures. Section 18.3 presents and discusses experimental results. Finally, Section 18.4 draws conclusions.

18.2 Experiments

18.2.1 Properties and size of CFRP/Ti stacks

Each of the CFRP/Ti stacks used in this study was formed by joining a CFRP plate (108 mm $\times$ 58 mm $\times$ 14 mm) and a Ti plate (108 mm $\times$ 58 mm $\times$ 7 mm) together using adhesive (Ultra Bond super glue, Permatex Inc., Solon, OH, USA). The CFRP was composed of carbon fibers and epoxy resin. Plain woven fabric of carbon fibers had an orientation of 0/90 degrees, as illustrated in Figure 18.2. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The CFRP contained 21 layers of fabric (42 layers of carbon fibers). The

Ti was titanium alloy (Ti-6Al-4V). Material properties of CFRP and Ti are listed in Table 18.1 and Table 18.2, respectively.

Figure 18.2 Illustration of woven fabric and CFRP structure.

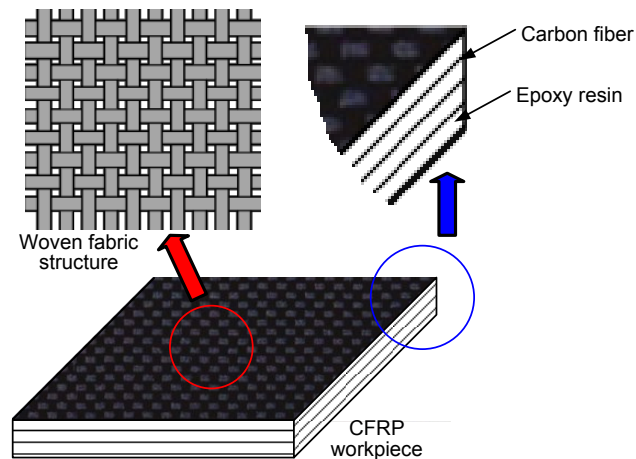


Table 18.1 Material properties of CFRP and its components.

Property	Unit	Value
Density of CFRP	kg/m ³	1550
Hardness (Rockwell)	HRB	70-75
Density of epoxy matrix	kg/m ³	1200
Elastic modulus of epoxy matrix	GPa	4.5
Tensile strength of epoxy matrix	MPa	130
Poisson's ratio of epoxy matrix		0.2
Density of carbon fiber	kg/m ³	1800
Elastic modulus of carbon fiber	GPa	230
Tensile strength of carbon fiber	GPa	5
Poisson's ratio of carbon fiber		0.3
Melting point of carbon fiber	°C	3552

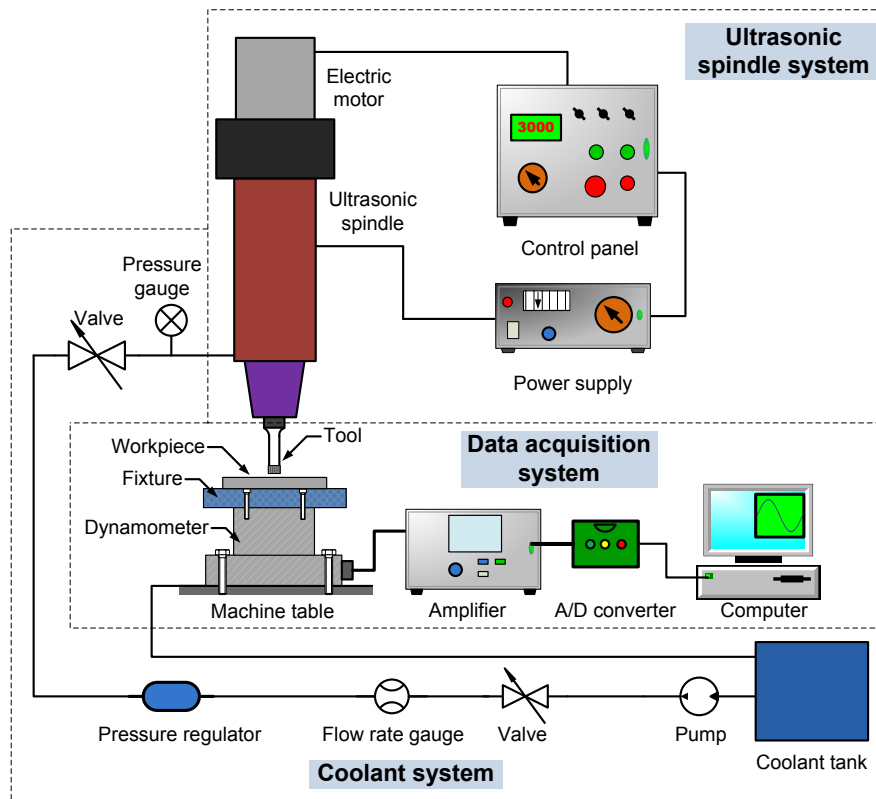
Table 18.2 Material properties of titanium alloy (Ti-6Al-4V).

Property	Unit	Value
Density	kg/m ³	4510
Hardness (Rockwell)	HRC	36
Elastic modulus	GPa	113.8
Tensile strength	MPa	950
Melting point	°C	1660

18.2.2 Experimental set-up

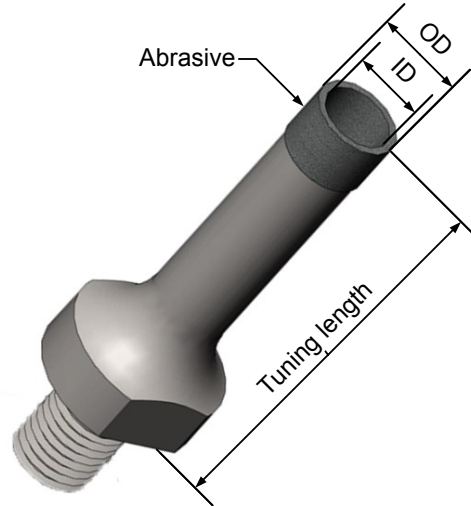
Experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 18.3. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system was comprised of an ultrasonic spindle, a power supply, and a control panel. The power supply converted conventional (60 Hz) electrical supply to high-frequency (20 kHz) electrical energy. This high-frequency electrical energy was converted into mechanical vibration by a piezoelectric converter. The vibration, after being amplified, was transmitted to the cutting tool, causing it to vibrate axially at the frequency of 20 kHz. The amplitude of ultrasonic vibration could be adjusted by changing the setting of output control of the power supply. The motor atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds could be obtained by adjusting the motor speed controller. The data acquisition system, including dynamometer, charge amplifier, A/D convertor, and computer with software, was used for measurement of cutting force and torque. More details about this system will be described in Section 18.2.4 (measurement procedures). The coolant system was comprised of pump, coolant tank, pressure regulator, flow rate and pressure gauges, and valves. It provided coolant to the spindle and the interface of machining.

Figure 18.3 RUM experimental set-up.



The cutting tools, as illustrated in Figure 18.4, were metal-bonded diamond core drills (NBR Diamond Tool Corp., LaGrangeville, NY, USA). The outer and inner diameters (OD and ID) of the cutting tools were 9.54 mm and 7.82 mm, respectively, and tuning length was 45 mm. The diamond abrasives had mesh size of 80/100 and concentration of 100. The metal bond was of B type.

Figure 18.4 Illustration of RUM tool.



18.2.3 Experimental conditions

Considering the limitations of the experimental set-up (for example, vibration frequency was fixed at 20 kHz on the machine), only two input variables were changed in the experiments:

- Ultrasonic power: Percentage of power from ultrasonic power supply to control the ultrasonic vibration amplitude (from 0 to 60% with an interval of 20%);
- Tool rotation speed: Rotational speed of the cutting tool (from 3000 to 7000 rpm with an interval of 1000 rpm).

In order to achieve good hole quality and maintain reasonable tool life, the optimal feedrate in RUM was below 0.05 mm/s for Ti [Cong et al., 2011a], but 0.5 mm/s for CFRP [Cong et al., 2011bc; 2012ab]. In this study, CFRP/Ti stacks were drilled with feedrate of 0.05 mm/s. The experimental conditions were listed in Table 18.3. Under each test condition, four drilling tests were conducted.

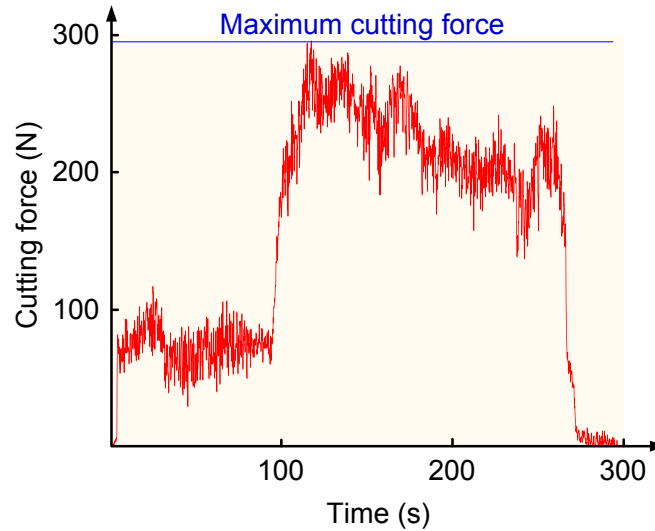
Table 18.3 Experimental conditions.

Feedrate (mm/s)	Tool rotation (RPM)	Ultrasonic %
0.05	4000	0
		20
		40
		60
	2000	40
	3000	
	4000	
	5000	
	6000	
	7000	

18.2.4 Measurement procedures

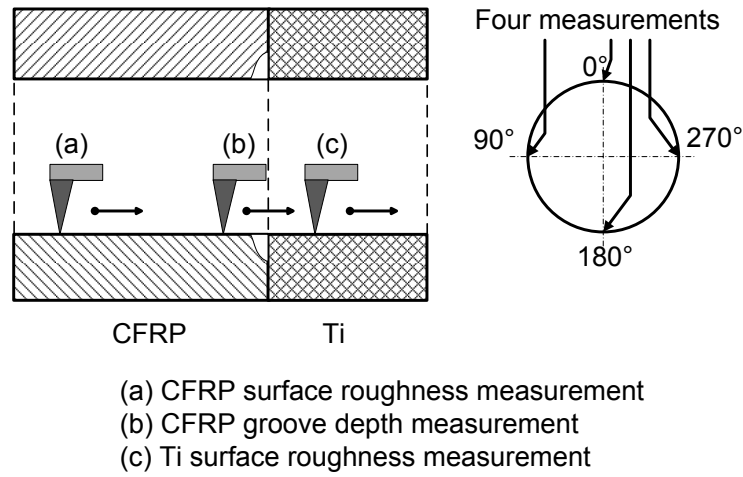
A dynamometer (Model 9272, Kistler Inc., Winterthur, Switzerland) was used to measure the cutting force in the axial direction and torque. The electrical signals from the dynamometer were amplified by a charge amplifier (Model 5070A, Kistler Inc., Winterthur, Switzerland) and then transformed into digital signals by an A/D converter. After being processed by a signal conditioner, the digital signals were collected by a data acquisition card (PC-CARD-DAS16/16, Measurement Computing Corporation, Norton, MA, USA) on a computer with the help of Dynoware software (Type 2815A, Kistler Inc., Winterthur, Switzerland). The sampling rate was 20 Hz. The measured cutting force fluctuated with time within a certain range, as illustrated in Figure 18.5. The maximum cutting force of the force-time curve was used to represent the cutting force for drilling of each hole. Similarly, the maximum torque of the torque-time curve was used to represent the torque for drilling of each hole.

Figure 18.5 A typical cutting force and time curve.



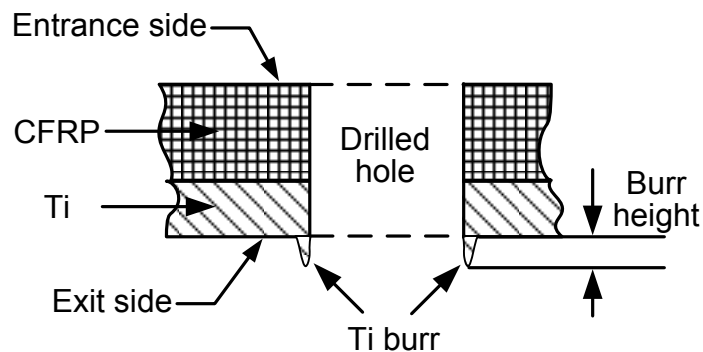
Surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan) was used to measure surface roughness of the hole surface and groove depth. Surface roughness was measured on the machined hole surface along the axial direction of the hole. The surface roughness reported in this paper was R_a (average surface roughness). Test range and cut-off length of surface roughness measurement were set at 4 mm and 0.8 mm, respectively. Groove depth (CFRP material near the interface between CFRP and Ti was overcut and a groove was formed) was measured on machined CFRP hole surface near the interface of CFRP and Ti. As illustrated in Figure 18.6, for both surface roughness and groove depth, four measurements were performed with 90° between two adjacent measurements. Each measurement was repeated twice. For each hole, there were eight values and the average of these eight values was used.

Figure 18.6 Surface roughness and groove depth measurements.



Ti exit burr height, as illustrated in Figure 18.7, was measured using an optical microscope (Model BX51 Olympus Inc. Tokyo, Japan). The maximum value of Ti exit burr height around the hole was used in this study. The eyepiece of the microscope had a magnification of 10 and the objective lens had a magnification of 10. Thus, the total magnification was 100.

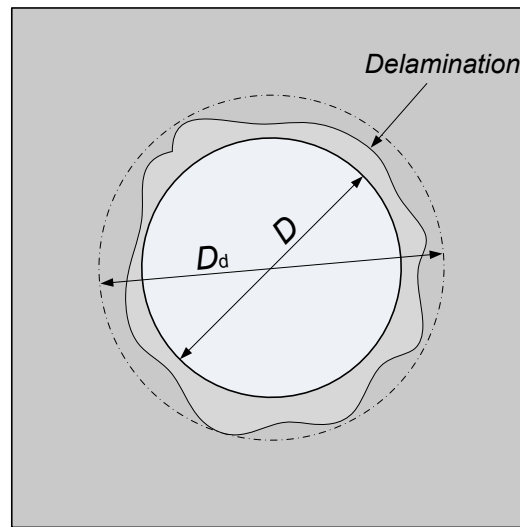
Figure 18.7 Illustrations of Ti exit burr and burr height.



Delamination factor [Tsao and Hocheng, 2004] was used to describe the degree of delamination of CFRP material at the entrance side. It was determined by D_d/D . Figure 18.8 illustrates both D_d and D . D is the hole diameter. D_d is the diameter of the smallest circle that

encloses all the delamination area around the hole. D_d and D were measured by a vernier caliper (model IP-65, Mitutoyo Corp., Kanagawa, Japan). Each measurement was performed once.

Figure 18.8 Measurement of delamination factor.



Hole size (diameter) variation measures the spread of hole diameter under the same test conditions for each method [Weiss. 1989]. In this paper, it is represented by the maximum hole diameter minus the minimum hole diameter among the holes drilled under each test condition. Hole diameters were measured using a vernier caliper (model IP-65, Mitutoyo Corp., Kanagawa, Japan). Similar to surface roughness and groove depth, four measurements were performed with 90° between two adjacent measurements. Each measurement was repeated twice. For each hole, there were eight values of hole diameter and the average of these eight values was used.

Tool life was defined as the number of holes a tool could drill without resharpening. It was calculated by the following formula:

$$\text{Tool life} = \frac{\text{Total weight of abrasive portion of the tool}}{\text{Average weight loss of the tool for one test}} \quad (1)$$

The weight of abrasive portion is the difference between weight of new tool and weight of tool without abrasive portion. The weight loss was the difference in the tool weight before and after the test. To remove any residuals left on the tool, the tool was cleaned using methanol and acetone and then dried using a hand dryer before measurement. The weight of the tool was measured by a high accuracy scale (Model APX-200, Denver Instrument, Denver, CO, USA).

18.3 Results and discussion

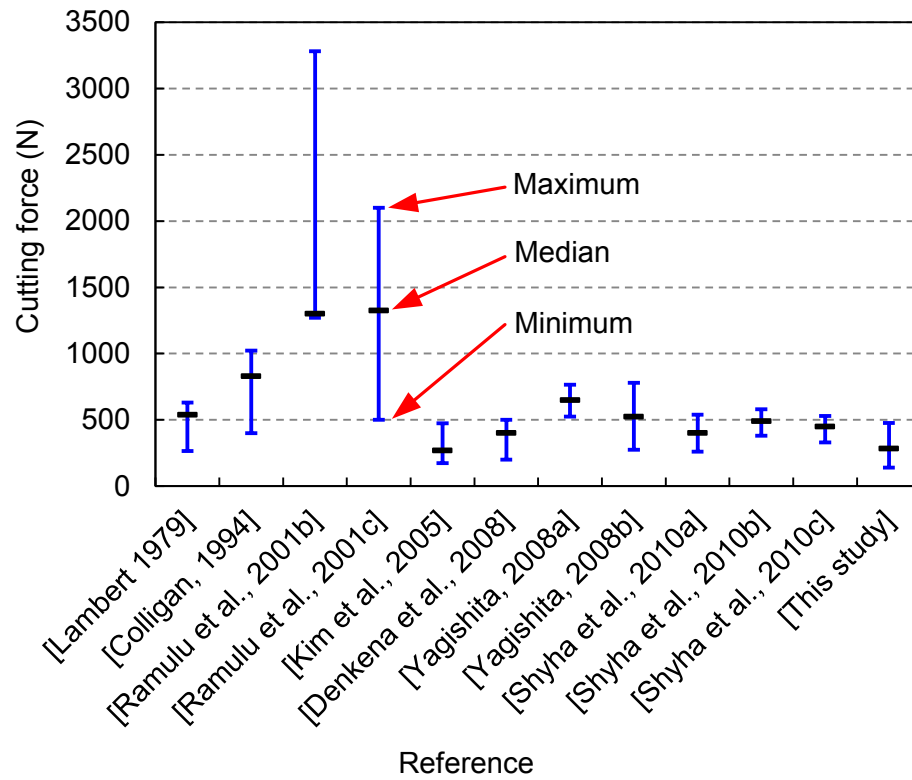
18.3.1 Cutting force

Cutting force in RUM of CFRP/Ti stacks under all test conditions in this study ranged from 140 to 477 N, with the median of 296 N, as shown in Figure 18.9. Reported cutting force data (including minimum, maximum, and median values) in drilling of CFRP/Ti stacks using other methods are also presented in Figure 18.9. Reported investigations using other methods are summarized in Table 18.4. It can be seen that the minimum, maximum, and median cutting forces using RUM were lower than (or equal to) those using other methods.

Table 18.4 Summary of reported investigations.

Reference	Hole diameter (mm)	Tool type	Thickness (mm) and material of workpiece
[This study]	9.6	Diamond core drills	14 CFRP / 7 Ti
[Lambert 1979]	6.35	Carbide twist drills	7.62 CFRP / 12.7 Ti
[Weiss, 1989]	6.35	Carbide twist drills	6.35 CFRP / 6.35 Ti
[Colligan, 1994]	7	Coated twist drills	CFRP / Ti, details unknown
[Kim et al., 2001a]	6.35	HSS twist drills	7.62 CFRP / 3.1 Ti
[Kim et al., 2001b]	6.35	Carbide twist drills	
[Ramulu et al., 2001a]	6.35	HSS twist drills	
[Ramulu et al., 2001b]	6.35	HSS twist drills	7.62 CFRP / 3.1 Ti
[Ramulu et al., 2001c]	6.35	Carbide twist drills	3 CFRP
[Davim and Reis, 2003a]	5	Carbide twist drills	
[Davim and Reis, 2003b]	5	Carbide twist drills	3.52 GFRP
[Khashaba, 2004a]	8	HSS twist drills	
[Khashaba, 2004b]	8	HSS twist drills	7.15 GFRP
[Kim et al., 2005]	Unknown	Carbide twist drills	Ti foils / Graphite / Ti foils
[Kim and Ramulu, 2005/7]	Unknown	Carbide twist drills	Ti foils / Graphite / Ti foils
[Garrick, 2007a]	6.35	Coated twist drills	7.72 CFRP / 6.15 Ti
[Garrick, 2007b]	6.35	Carbide twist drills	
[Denkena et al., 2008]	8	Coated carbide end mills	6 CFRP / 11 Ti
[Yagishita, 2008a]	6	Carbide twist drills	4 CFRP / 3 Ti
[Yagishita, 2008b]	5	Coated carbide end mills	
[Quan and Sun, 2010]	4	Carbide twist drills	3.5 CFRP
[Shyha et al., 2010a]	6.35	Carbide twist drills	30 Ti / 30 CFRP / 30 Al
[Shyha et al., 2010b]	6.35	Coated twist drills	
[Shyha et al., 2010c]	6.35	Carbide twist drills	
[Zitoune, et al., 2010]	6 & 8	Carbide twist drills	4.2 CFRP / 3 Al

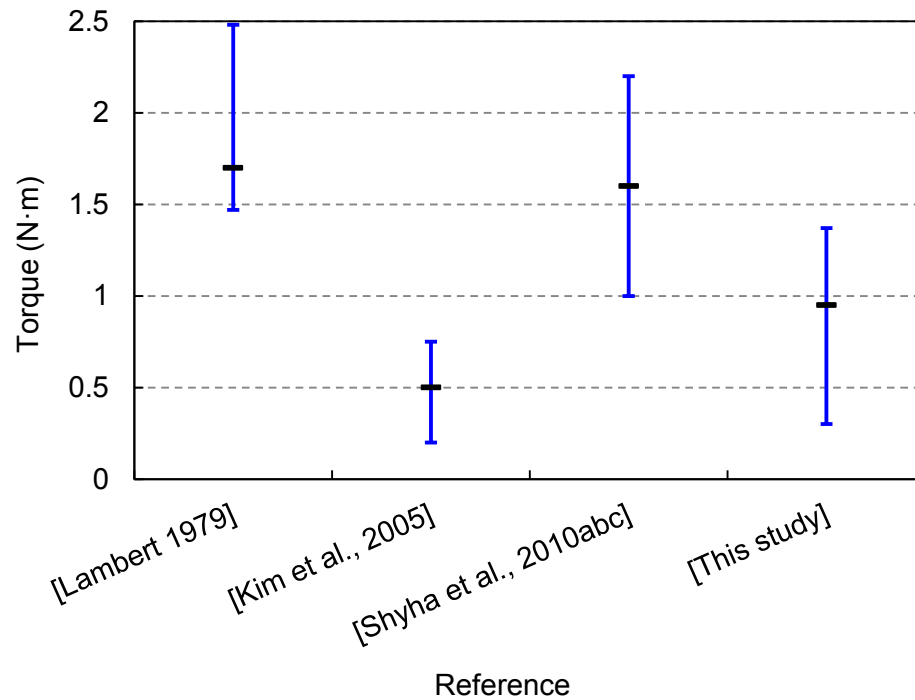
Figure 18.9 Comparison of cutting force.



18.3.2 Torque

The minimum, maximum, and median values of torque in RUM of stacks were 0.3, 1.37, and 0.95 N·m, respectively. As shown in Figure 18.10, these torque values were lower than those in drilling CFRP/Ti stacks or Ti/CFRP/Al stacks using other methods [Lambert, 1979; Shyha et al., 2010]. Drilling of Ti foils/graphite/Ti foils workpiece resulted in lower torque values to those obtained this study [Kim et al., 2005]. Please note that the thickness of Ti foils in Kim et al.'s study was about 0.1 mm. In comparison, the thickness of the Ti workpiece in this study was 8 mm.

Figure 18.10 Comparison of torque.

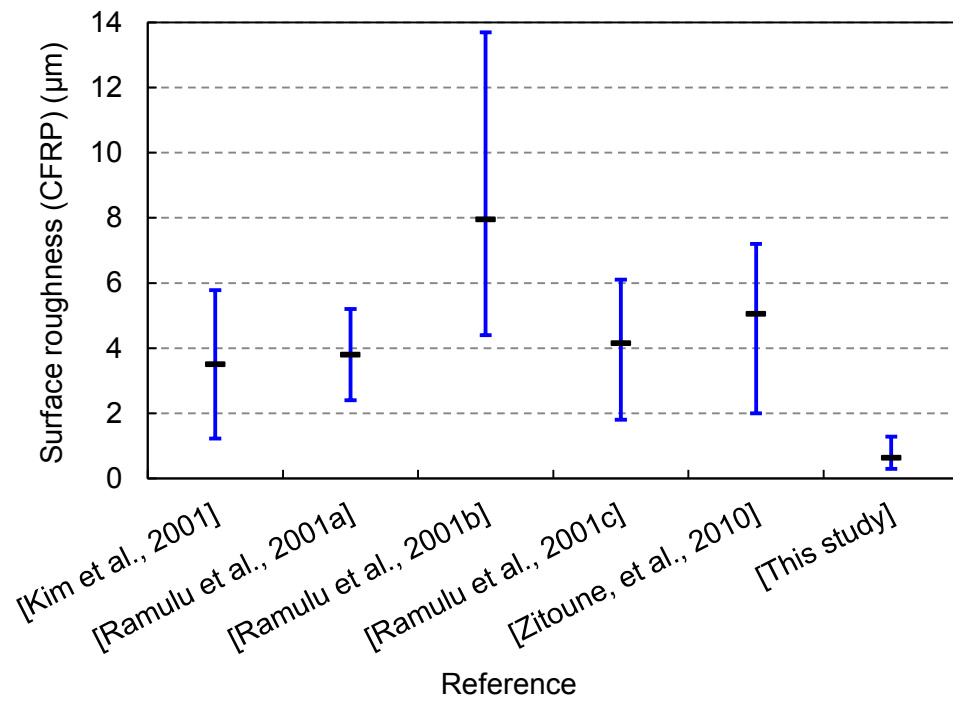


18.3.3 Surface roughness

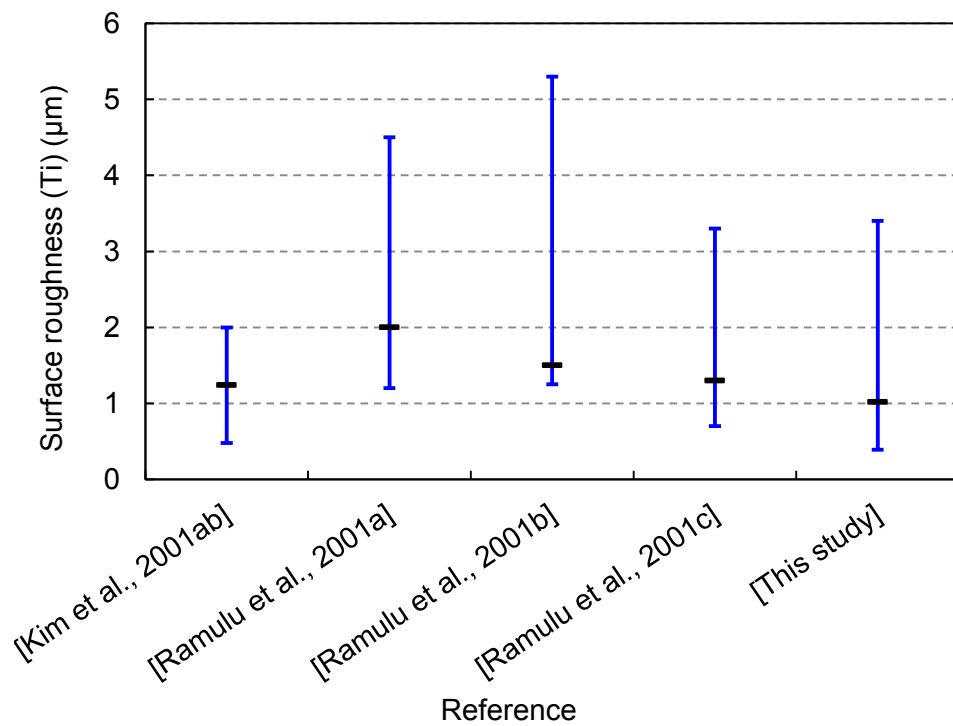
Figure 18.11 compares surface roughness in drilling of CFRP/Ti stacks using RUM and other methods.

Surface roughness on CFRP holes drilled using RUM ranged from 0.3 to 1.29 μm with the median of 0.635 μm . As shown in Figure 18.11(a), surface roughness values on CFRP holes using RUM were lower than those using other methods.

Figure 18.11 Comparison of surface roughness.



(a) On machined CFRP surface



(b) On machined Ti surface

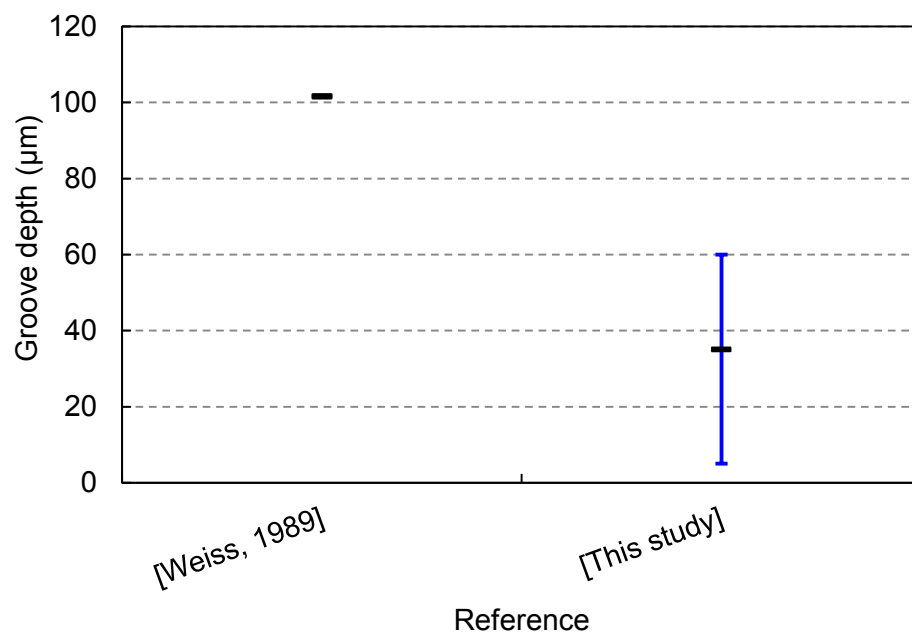
Surface roughness on Ti holes drilled using RUM ranged from 0.39 to 3.4 μm with the median of 1.02 μm . As shown in Figure 18.11(b), these values were similar to those using other

methods [Kim et al., 2001ab; Ramulu et al., 2001abc]. In this study, the test range of 4 mm, the recommended setting of the surface profilometer, was used in surface roughness measurement. However, the test range in surface roughness measurement in reported studies using other methods would be smaller, because the Ti workpiece thickness in these investigations was 3.1 mm (smaller than the 4 mm test range used in this study). Different surface roughness values might be obtained for the same surface if different test ranges were used [Bhushan, 2002].

18.3.4 CFRP groove depth

Figure 18.12 compares CFRP groove depth in drilling of CFRP/Ti stacks using RUM and method reported by Weiss [1989]. The range of CFRP groove depth using RUM was from 5 to 30.78 μm with the median of 35 μm . The median value of groove depth using carbide twist drills was 101.6 μm [Weiss, 1989].

Figure 18.12 Comparison of CFRP groove depth.



18.3.5 Ti exit burr

Figure 18.13 shows a top-view picture of the Ti exit side of a hole drilled using RUM. There was no observable burr. Figure 18.14 compares burr height in drilling of CFRP/Ti stacks using RUM and other methods. There was always burr using other methods.

Figure 18.13 Top view of Ti exit side of a hole drilled using RUM.

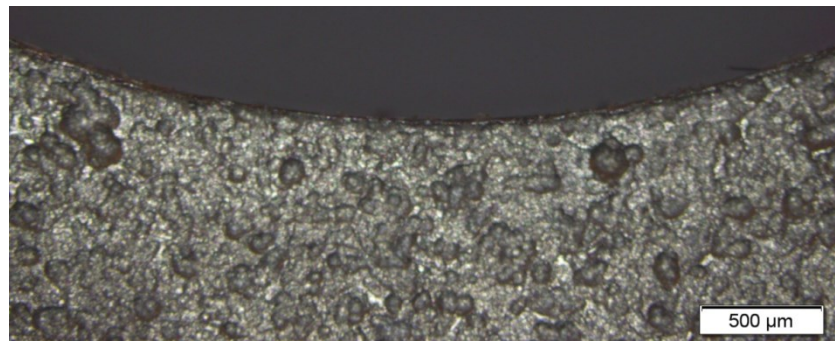
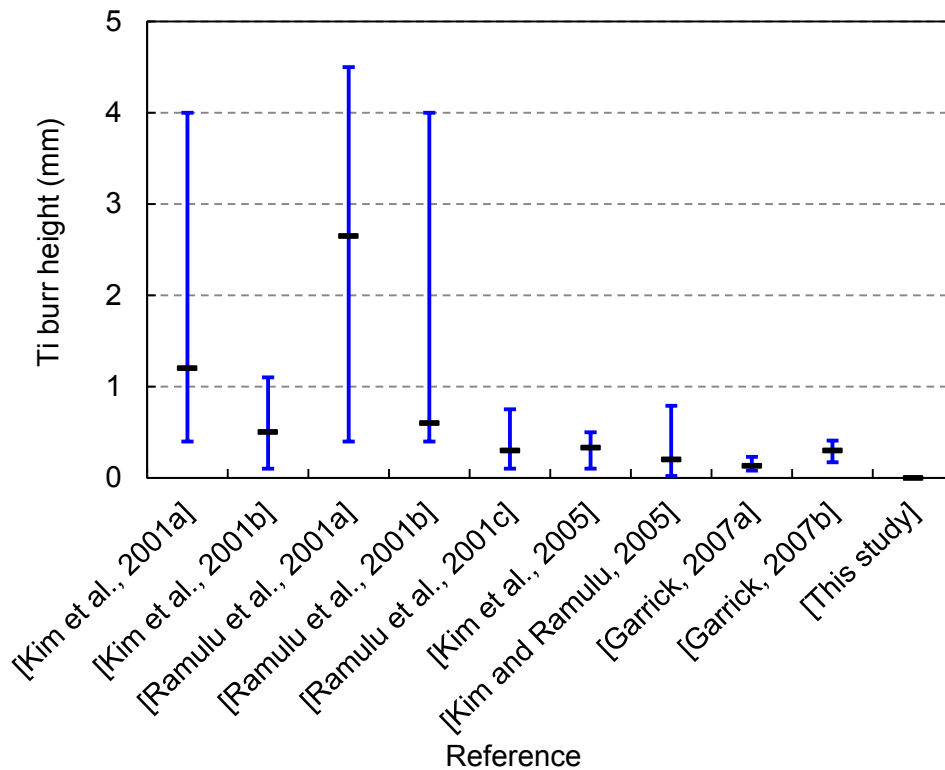


Figure 18.14 Comparison of Ti burr height.



18.3.6 CFRP entrance delamination

Figure 18.15 shows a top-view picture of the CFRP entrance side of a hole drilled using RUM. No entrance delamination could be observed.

Figure 18.15 Top view of CFRP entrance side of a hole drilled using RUM.

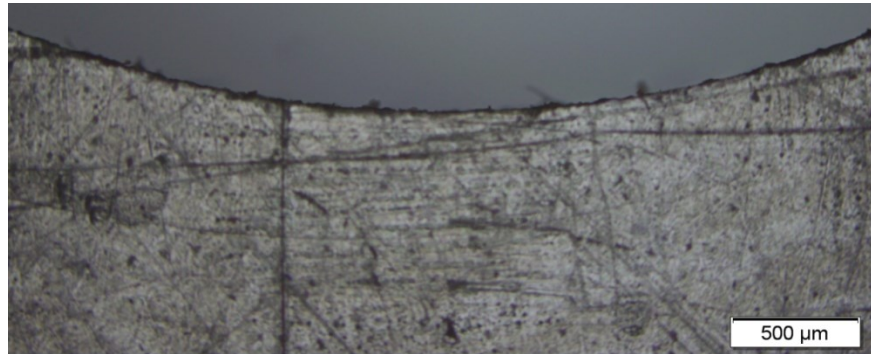
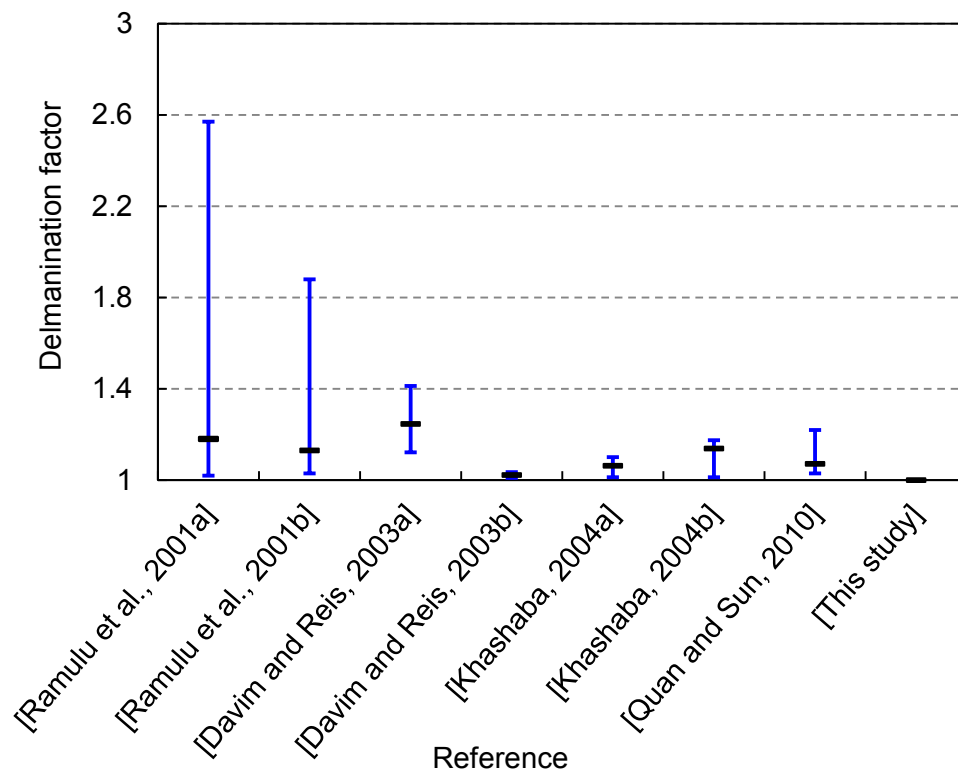


Figure 18.16 Comparison of CFRP entrance delamination.



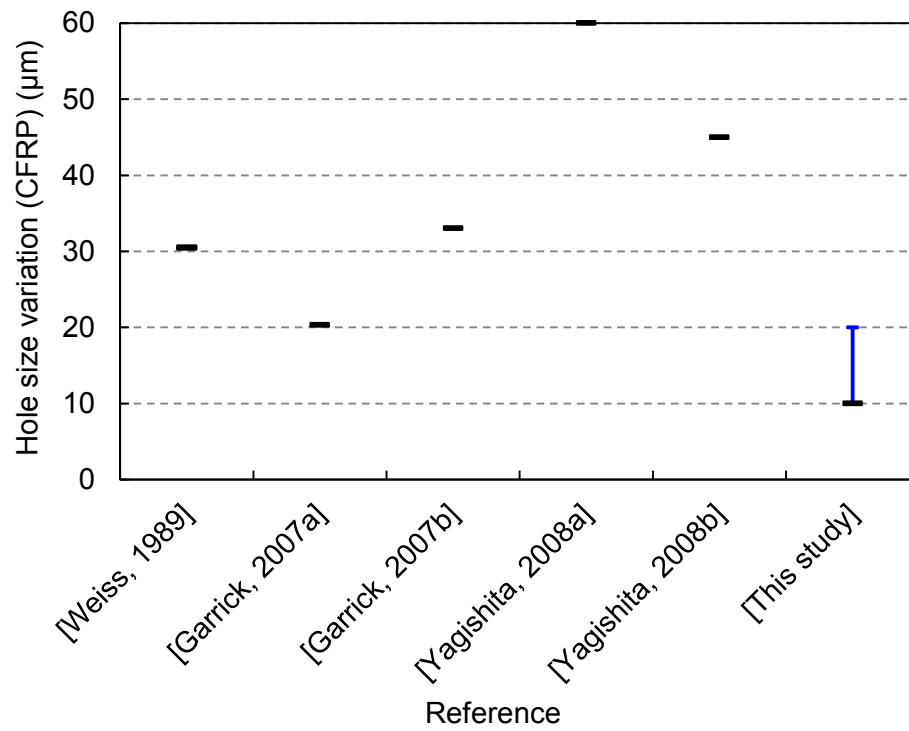
Comparison of CFRP entrance delamination in drilling of CFRP/Ti stacks (or CFRP plates) using RUM and other methods is shown in Figure 18.16. Since there was no entrance delamination in drilling of CFRP/Ti stacks using RUM, the delamination factor was one. However, CFRP entrance delamination was always observed using other methods. Note that some data in the figure [Davim and Reis, 2003ab; Quan and Sun, 2010] were obtained from drilling of CFRP plates (not CFRP/Ti stacks).

18.3.7 Hole size variation

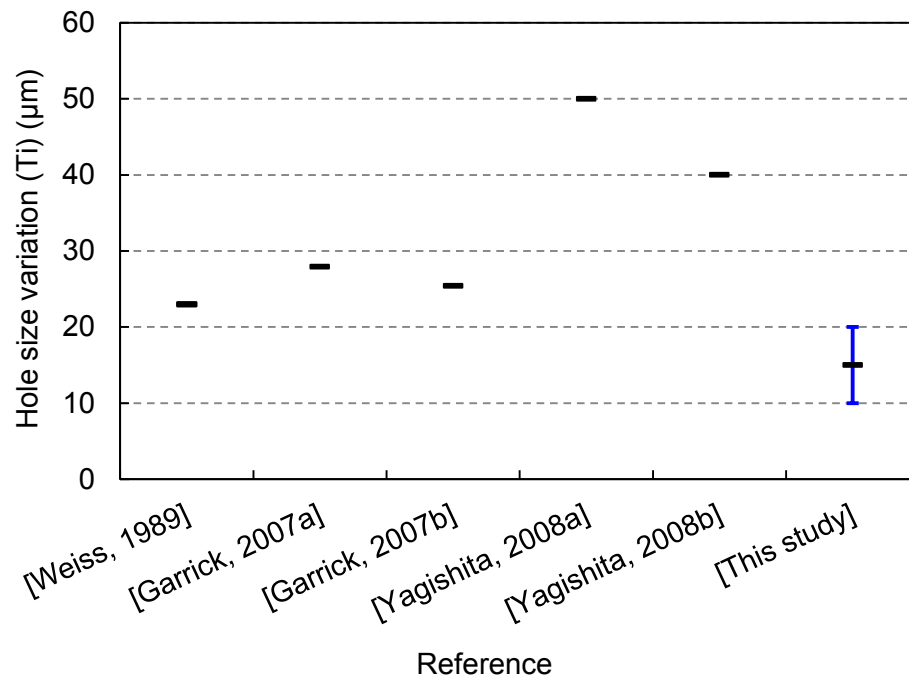
The comparison of CFRP hole size variation in drilling of CFRP/Ti stacks using RUM and other methods is shown in Figure 18.17(a). CFRP hole size variation in RUM of CFRP/Ti stacks under all test conditions in this study ranged from 10 to 20 μm , with the median of 10 μm those were smaller than those in other methods.

The comparison of Ti hole size variation in drilling of CFRP/Ti using RUM and other methods is shown in Figure 18.17(b). Ti hole size variation in RUM of CFRP/Ti stacks under all test conditions in this study ranged from 10 to 20 μm , with the median of 15 μm . It also can be seen that the minimum, maximum, and median Ti hole size variation using RUM were smaller than those using other methods.

Figure 18.17 Comparison of hole size variation.



(a) For CFRP

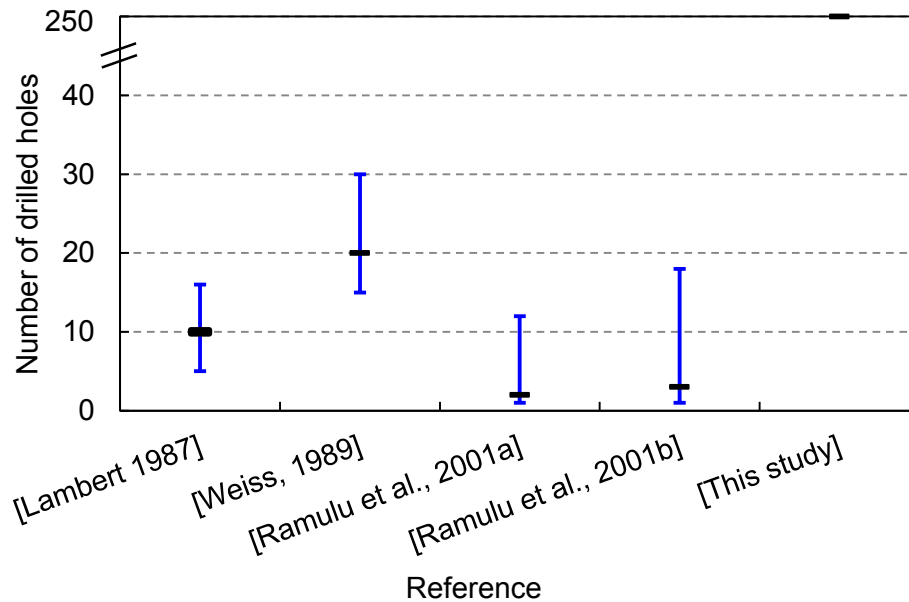


(b) For Ti

18.3.8 Tool life

Figure 18.18 compares tool life in drilling of CFRP/Ti stacks using RUM and other methods. About 250 holes could be drilled using RUM, while the numbers of holes a tool could drill without resharpener using other studies were much smaller, ranging from 4 to 20 [Lambert, 1987; Weiss, 1989; Ramulu et al., 2001a; Ramulu et al., 2001b].

Figure 18.18 Comparison of tool life.



18.4 Conclusions

This paper reports a study on drilling of CFRP/Ti stacks using rotary ultrasonic machining (RUM). It compares cutting force, torque, surface roughness, CFRP groove depth, Ti exit burr height, CFRP entrance delamination, hole size variation, and tool life using RUM with those in the literature using other methods. The following conclusions can be drawn from this study:

1. Compared with other methods for drilling of CFRP/Ti stacks, RUM resulted in lower cutting force and CFRP surface roughness, smaller groove depth and hole size variation

(for both CFRP and Ti), and longer tool life.

2. There was no obvious Ti exit burr and CFRP entrance delamination when using RUM to drill CFRP/Ti stacks.
3. Ti surface roughness in drilling of CFRP/Ti stacks using RUM was about the same as those using other methods.

Acknowledgements

The work was supported by the National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to N.B.R. Diamond Tool Corp. for supplying the diamond core drills.

References

[Boeing website] 787 Dreamliner Program Fact Sheet, available at: <http://www.boeing.com/commercial/787family/programfacts.html>, Accessed on June 24, 2012.

[Bhushan, 2002] Bhushan B., 2002, Introduction of Tribology, First edition, John Wiley & Sons, Inc., Hoboken, NJ, USA.

[Brinksmeier and Janssen, 2002] Brinksmeier E., and Janssen R., 2002, Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys, CIRP Annals - Manufacturing Technology, 51(1), pp. 87-90.

[Chung, 2010] Chung D.D.L., 2010, Composite Materials Science and Applications, Second edition, Springer-Verlag London Ltd., London, UK.

[Churi et al., 2005] Churi N.J., Li Z.C., Pei Z.J., and Treadwell C., 2005, Rotary ultrasonic machining of titanium alloy: a feasibility study. Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition (IMECE 2005), Orlando, FL, USA, November 5-11, pp. 885-892,

[Churi et al., 2006] Churi N.J., Pei Z.J., and Treadwell C., 2006, Rotary ultrasonic machining of titanium alloy: effects of machining variables, *Machining Science and Technology* 10(3), pp. 301-321.

[Churi et al., 2007a] Churi N.J., Pei Z.J., and Treadwell C., 2007a, Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables, *International Journal of Precision Technology*, 1(1), pp. 85-96.

[Churi et al., 2007b] Churi N.J., Pei Z.J., and Treadwell C., 2007b, Wheel wear mechanisms in rotary ultrasonic machining of titanium, Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition (IMECE 2007), Seattle, WA, USA, November 11-15, pp. 399-407.

[Colligan, 1994] Colligan K., 1994, New tool drills both titanium and carbon composites, *American Machinist*, (10), pp.56-58.

[Cong et al., 2011a] Cong W.L., Pei Z.J., Feng Q., Deines T.W., and Treadwell C., 2011, Experimental study on cutting temperature in rotary ultrasonic machining, Proceedings of NAMRI/SME, 39, pp. 369-376.

[Cong et al., 2011b] Cong W.L., Pei Z.J., Deines T.W., and Treadwell C., 2011, Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions, *Journal of Reinforced Plastics and Composites*, 30(10), pp. 899-906.

[Cong et al., 2011c] Cong W.L., Feng Q., Pei Z.J., Deines T.W., and Treadwell C., 2011, Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables, Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference (MSEC), Corvallis, OR, USA, June 13-17, MSEC2011-50116.

[Cong et al., 2012a] Cong W.L., Pei Z.J., Feng Q., Deines T.W., and Treadwell C., 2012, Rotary ultrasonic machining of CFRP: a comparison with twist drilling, Journal of Reinforced Plastics and Composite, 31(5), pp. 313-321.

[Cong et al., 2012b] Cong W.L., Pei Z.J., Feng Q., Deines T.W., and Treadwell C., 2012, Rotary ultrasonic machining of carbon fiber reinforced plastic composites: using cutting fluid versus cold air as coolant, Journal of Composite Materials, 46(14), pp. 1747-1753.

[Davim and Reis, 2003] Davim J.P., and Reis P., 2003, Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, Materials and Design, 24(5), pp. 315-324.

[Denkena et al., 2008] Denkena B., Boehnke D., and Dege J.H., 2008, Helical milling of CFRP-titanium layer compounds, CIRP Journal of manufacturing Science and Technology, 1(2), pp. 64-69.

[Garrick, 2007] Garrick R., 2007, Drilling advanced aircraft structures with PCD (Polycrystalline Diamond) Drills, AeroTech Congress & Exhibition, Los Angeles, CA, USA, September 18-20.

[Guu et al., 2001] Guu Y.H., Hocheng H., Tai N.H., and Liu S.Y., 2001, Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, Journal of Materials Science, 36(8), pp. 2037-2043.

[Khashaba, 2004] Khashaba U.A., 2004, Delamination in drilling GFR-thermoset composites, *Composite Structures*, 63(3-4), pp.313-327.

[Kim and Lee, 2005] Kim G.W., and Lee K.Y., 2005, Critical thrust force at propagation of delamination zone due to drilling of FRP/metallic strips, *Composite Structures*, 69(2), pp. 137-141.

[Kim and Ramulu, 2004] Kim D., and Ramulu M., 2004, Drilling process optimization for graphite/bismaleimide-titanium alloy stacks, *Composite Structures*, 63(1), pp. 101-114.

[Kim and Ramulu, 2005] Kim D., and Ramulu M., 2005, Cutting and drilling characteristics of hybrid titanium composite laminate (HTCL), 37th Proceedings of materials and processing technologies for revolutionary applications fall technical conference, Seattle, WA, USA, October 31 - November 3, pp. 1-8.

[Kim and Ramulu, 2005] Kim D., and Ramulu M., 2005, Study on the drilling of Titanium/Graphite hybrid composites, ASME International Mechanical Engineering Congress and Exposition, Orlando, FL, USA, November 5-11, pp. 99-106.

[Kim and Ramulu, 2005] Kim D., and Ramulu M., 2005, Study on the drilling of titanium/Graphite hybrid composites, *Journal of Engineering Materials and Technology*, 129(3), pp. 390-396.

[Kim et al. 2001] Kim D., Ramulu M., and Garbini J., 2001, Hole quality in drilling of Graphite/Bismaleimide-Titanium stacks, 33rd International SAMPE Technical Conference, Seattle, WA, USA, November 5-8, pp. 1315-1326.

[Kim et al., 2005] Kim D., Ramulu M., and Pedersen W., 2005, Machinability of titanium/graphite hybrid composites in drilling, *Transactions of NAMRI/SME*, 33, pp. 445-452.

[Lambert, 1987] Lambert B.K., 1987, Cutting and drilling of composite materials, The Carbide and Tool Journal, 19(5), pp. 31-34.

[Li et al., 2007] Li Z.C., Pei Z.J., Sisco T., Micale A.C., and Treadwell C., 2007, Experimental study on rotary ultrasonic machining of graphite/epoxy panel, ASPE Spring Topical Meeting on Vibration Assisted Machining Technology, Chapel Hill, NC, USA, April 16-17, pp. 52-57.

[Mallick, 1997] Mallick P.K., 1997, Composite Engineering Handbook, Marcel Dekker Inc., New York, NY, USA.

[Margolis 2006] Margolis D., Stacking the odds, Cutting Tool Engineering, (8), 74-80.

[Quan and Sun, 2010] Quan Y., and Sun L., 2010, Investigation on drilling induced delamination of CFRP with infiltration method, Advanced Materials Research, 139-141, pp. 55-58.

[Ramulu et al., 2001] Ramulu M., Branson T., and Kim D., 2001, A study on the drilling of composite and titanium stacks, Composite Structures, 54(10), pp. 67-77.

[Sadat, 1995] Sadat, A.B., 1995, Delamination and other types of damage of graphite/epoxy composite caused by machining, American Society of Mechanical Engineers, Applied Mechanics Division, 208, pp. 41-52.

[Schwartz, 1992] Schwartz, M.M., 1992, Composite Materials Handbook, Second edition, McGraw-Hill, Columbus, OH, USA.

[Shyha et al., 2010] Shyha I.S., Soo S.L., Aspinwall D.K., Bradley S., Dawson S., and Pretorius C.J., 2010, Drilling of titanium/CFRP/Aluminum stacks, Key Engineering Materials, 447-448, pp. 624-633.

[Weiss, 1989] Weiss R.A., 1989, Portable air feed peck drilling of graphite composite, titanium and other materials in dissimilar combinations, FASTEC '89, Arlington, Texas, USA, October 4-6.

[Yagishita, 2008] Yagishita H., Comparing drilling and circular milling for hole making in bi-layer composite materials consisting of carbon fiber reinforced plastic (CFRP) laminates and titanium alloys, Transactions of NAMRI/SME, 36, pp. 17-24.

[Zitoun et al., 2010] Zitoun R., Krishnaraj V., and Collombet F., 2010, Study of drilling of composite material and aluminium stack, Composite Structures, 92(5), pp. 1246-1255.

Chapter 19 - CFRP/Ti Stacks - Effects of Two Feedrate Types

Paper title:

Rotary ultrasonic machining of CFRP/Ti stacks: using variable feedrate

Submitted to:

Composite Part B

Authors' names:

Cong, W.L.¹, Pei, Z.J.¹, Deines, T.W.¹, Liu, D.F.² and Treadwell C.³

Authors' affiliations:

1. Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
2. College of Mechanical and Electrical Engineering, Central South University, Changsha, Hunan 410083, China
3. Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Abstract

Rotary ultrasonic machining (RUM) has been successfully used to drill Ti (titanium and its alloy), CFRP (carbon fiber reinforced plastic composite), and CFRP/Ti stacks. In all studies on RUM reported in the literature, feedrate was fixed during each experimental test. It has been shown that low feedrate should be used for RUM of Ti, but RUM of CFRP could be done using feedrate ten times higher. This paper, for the first time, reports a study on RUM of CFRP/Ti stacks using variable feedrate (higher feedrate for CFRP and lower feedrate for Ti). It also makes comparisons on RUM of CFRP/Ti stacks using fixed and variable feedrate.

Keywords: Rotary ultrasonic machining, CFRP/Ti stack, Fixed feedrate, Variable feedrate, Drilling, Grinding.

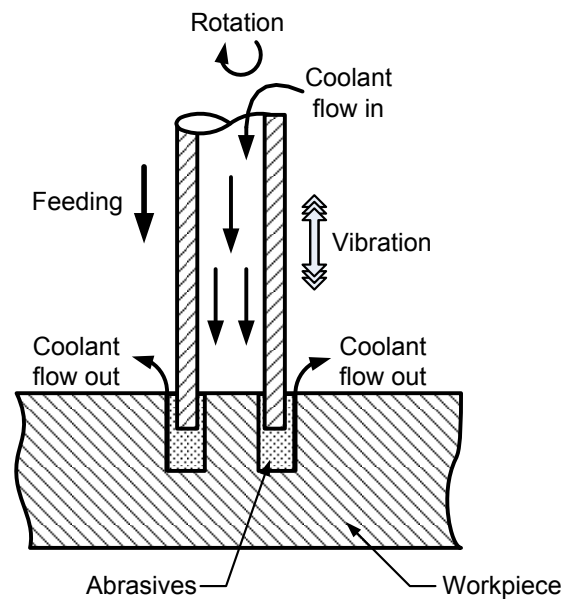
19.1 Introduction

To decrease fuel consumption, increase aircraft life, and save maintenance cost, carbon fiber reinforced plastic (CFRP) composites are increasingly used in the aircraft industry [Denkena et al., 2008; Davim and Reis, 2003, Lambert, 1987; Sadat, 1995; Guu et al., 2001; Chung, 2010] [Borchure, 2009; Mangalgiri, 1999; Cookson, 2009; Denkena et al., 2008; Garrick, 2007; Kanirura, 2005]. In aircraft assembly, bolting and riveting are currently the preferred methods for fastening CFRP and Ti structural parts [Bennett, 1985, Ramulu et al., 2001; Shyha 2010]. As a result, a large number of holes need to be drilled in CFRP/Ti stacks [Shyha 2010; Boeing web, Zitoune et al., 2010; Ramulu et al., 2001; Massarweh et al, 1992; Shyha 2010; Lambert, 1979].

Problems in drilling of CFRP/Ti stacks using traditional methods include high cutting force and torque [Ramulu et al., 2001; Lambert, 1979], high tool wear [Lambert, 1979; Ramulu et al., 2001; Weiss 1989], high surface roughness [Kim et al., 2001; Ramulu et al., 2001], and

large groove depth in composite [Weiss 1989]. Rotary ultrasonic machining (RUM) could be a solution to overcome these problems. RUM is illustrated in Figure 19.1. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrates axially at an ultrasonic frequency and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf, and prevents the tool from jamming and overheating.

Figure 19.1 Illustration of rotary ultrasonic machining.



RUM has been successfully used to drill Ti [Churi et al. 2005, 2006, 2007ab; Cong et al., 2011_Ti], CFRP [Li et al. 2007; Cong et al, 2011, 2012ab], and CFRP/Ti stacks [feasibility study]. In all studies on RUM reported in the literature, feedrate was fixed during each experimental test. It has been shown that, in order to achieve good quality and reasonable tool life, low feedrate (below 0.05 mm/s) should be used in RUM of Ti [Cong et al., 2011a], but feedrate in RUM of CFRP could be ten time higher [Cong et al., 2011bc; 2012ab]. When RUM

of CFRP/Ti stacks, if a fixed low feedrate is used, cycle time will be too long; if a fixed high feedrate is used, tool life will be too short. A solution to this dilemma is to use variable feedrate (high feedrate for CFRP and low feedrate for Ti). This paper presents results of such a study. It also makes comparisons on RUM of CFRP/Ti stacks using fixed feedrate and variable feedrate.

There are four sections in this paper. Following this introduction section, Section 19.2 describes workpiece material properties, experimental set-up, and measurement procedures. Section 19.3 presents and discusses experimental results. Finally, Section 19.4 draws conclusions.

19.2 Experiments

19.2.1 Properties of workpiece materials

CFRP/Ti stacks used in this study were formed by joining a CFRP plate (108 mm $\times$ 58 mm $\times$ 14 mm) and a Ti plate (108 mm $\times$ 58 mm $\times$ 7 mm) together using adhesive (Ultra Bond super glue, Permatex Inc., Solon, OH, USA). The CFRP was composed of carbon fibers and epoxy resin matrix. Plain woven fabric of carbon fibers had an orientation of 0/90 degrees, as illustrated in Figure 19.2. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The CFRP contained 21 layers of fabric (42 layers of carbon fiber). The Ti workpiece material was titanium alloy (Ti-6Al-4V). Material properties of CFRP and Ti are listed in Table 19.1 and Table 19.2, respectively.

Figure 19.2 Illustrations of woven fabric and CFRP structures.

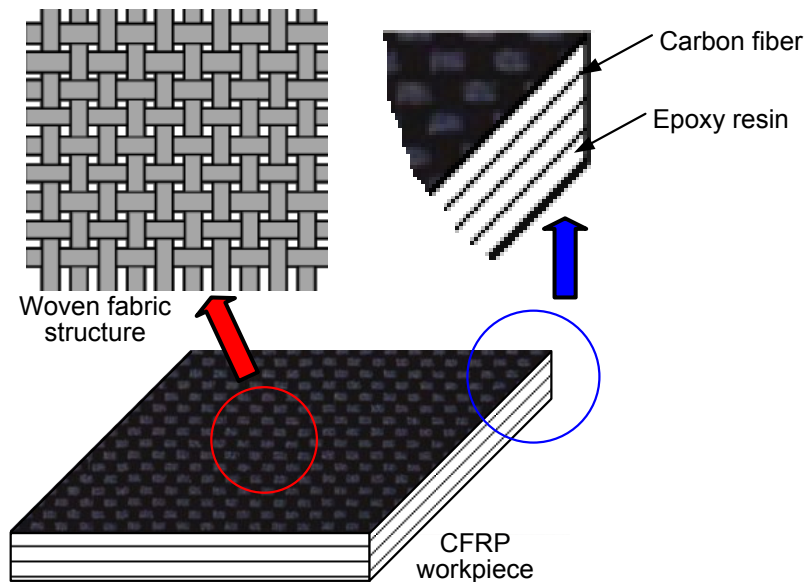


Table 19.1 Material properties of CFRP and its components.

Property	Unit	Value
Density of CFRP	kg/m ³	1550
Hardness (Rockwell)	HRB	70-75
Density of epoxy matrix	kg/m ³	1200
Elastic modulus of epoxy matrix	GPa	4.5
Tensile strength of epoxy matrix	MPa	130
Poisson's ratio of epoxy matrix		0.2
Density of carbon fiber	kg/m ³	1800
Elastic modulus of carbon fiber	GPa	230
Tensile strength of carbon fiber	GPa	5
Poisson's ratio of carbon fiber		0.3
Melting point of carbon fiber	°C	3552

Table 19.2 Material properties of titanium alloy (Ti-6Al-4V).

Property	Unit	Value
Density	kg/m ³	4510
Hardness (Rockwell)	HRC	36
Elastic modulus	GPa	113.8
Tensile strength	MPa	950
Melting point	°C	1660

19.2.2 Experimental set-up

Experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 19.3. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system was comprised of an ultrasonic spindle, a power supply, an electric motor, and a control panel. The power supply converted conventional (60 Hz) electrical supply to high-frequency (20 kHz) electrical energy. This high-frequency electrical energy was provided to a piezoelectric converter that changed high-frequency electrical energy into mechanical vibration. The ultrasonic vibration from the converter was amplified and transmitted to the cutting tool. This caused the cutting tool to vibrate axially at the frequency of 20 kHz. The amplitude of ultrasonic vibration could be adjusted by changing the level of output control of the power supply. The motor atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds could be obtained by adjusting the motor speed controller on the control panel. The data acquisition system, including dynamometer, charge amplifier, A/D convertor, and computer with software, was used for measurement of cutting force and torque. More details about this system will be described in Section 2.4 (measurement procedures). The coolant system was comprised of pump, coolant tank, pressure regulator, flow rate and pressure gauges, and valves. The coolant system provided coolant to the spindle and the interface of machining.

The cutting tools, as illustrated in Figure 19.4, were metal-bonded diamond core drills (N.B.R. Diamond Tool Corp., LaGrangeville, NY, USA). The outer and inner diameters (OD and ID) of the cutting tools were 9.54 mm and 7.82 mm, respectively, and the tuning length was 45 mm. The diamond abrasives had mesh size of 80/100 and concentration of 100. The metal bond was of B type.

Figure 19.3 RUM experimental set-up.

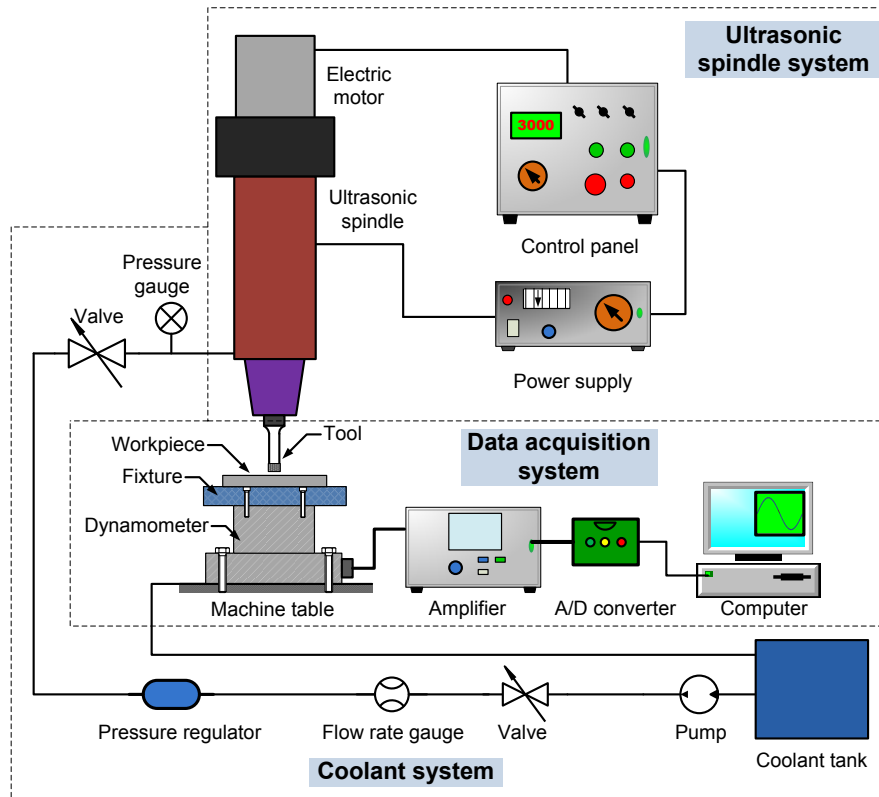
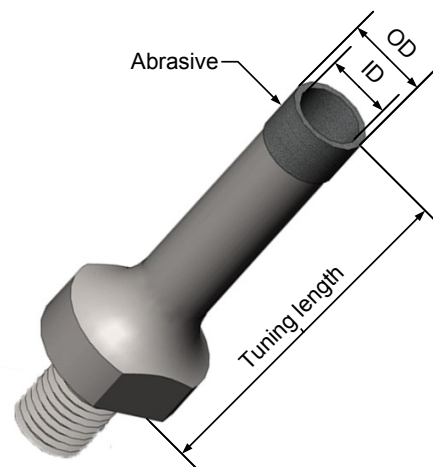


Figure 19.4 Illustration of RUM cutting tool.



19.2.3 Experimental conditions

Considering the limitations of the experimental set-up (for example, vibration frequency was fixed at 20 kHz on the machine), only the following input variables were changed in the experiments:

- Ultrasonic power: Percentage of power from ultrasonic power supply to control the ultrasonic vibration amplitude;
- Tool rotation speed: Rotational speed of cutting tool;
- Feedrate: Feedrate of cutting tool.

Values of these input variables used in this study are listed in Table 19.3.

Two types of feedrate were used. If using fixed feedrate, the entire hole was drilled using a feedrate of 0.05 mm/s. If using variable feedrate, feedrate of 0.5 mm/s was used to drill CFRP and feedrate of 0.05 mm/s was used to drill Ti. Feedrate was changed from 0.5 mm/s to 0.05 mm/s during a period of 10 s towards the end of CFRP machining. Figure 19.5 compared these two different types of feedrate as a function of feeding depth (the distance between workpiece top surface and tool-workpiece interface, as illustrated in Figure 19.6).

Table 19.3 Input variables and their values.

Variable	Unit	Value
Ultrasonic power	%	0; 20; 40; 60
Tool rotation speed	rpm	2000; 3000; 4000; 5000; 6000; 7000
Feedrate	mm/s	0.05 (Fixed); 0.5 / 0.05 (Variable)

Figure 19.5 Illustrations of fixed feedrate and variable feedrate.

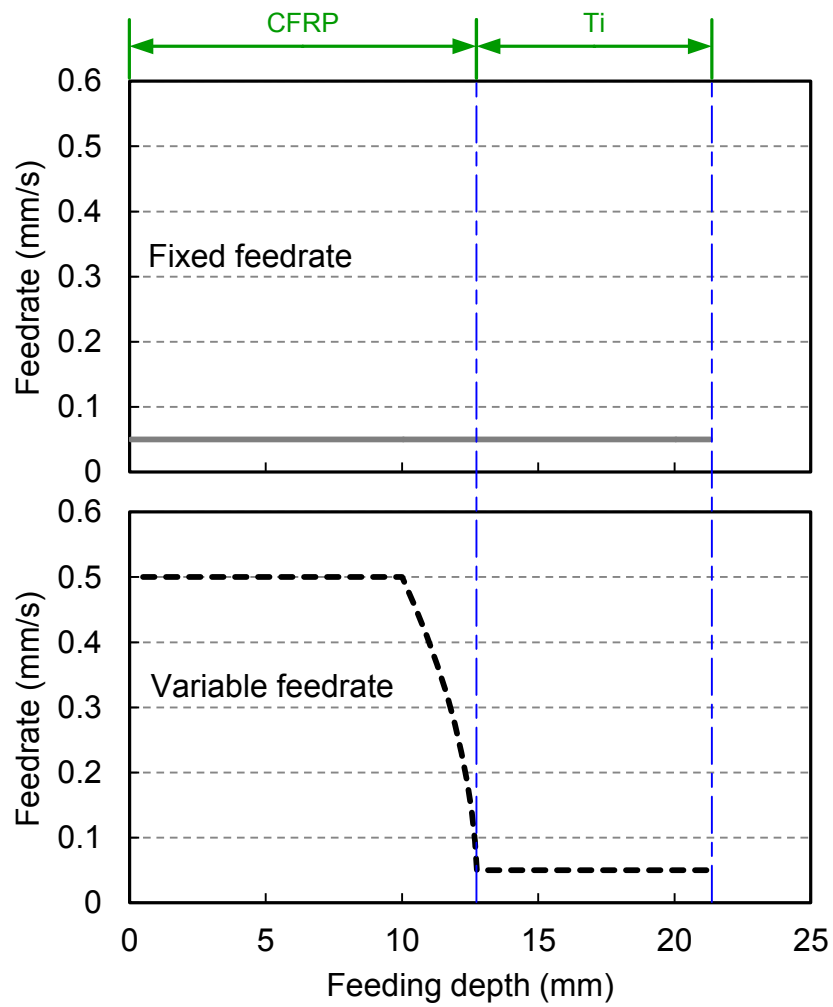
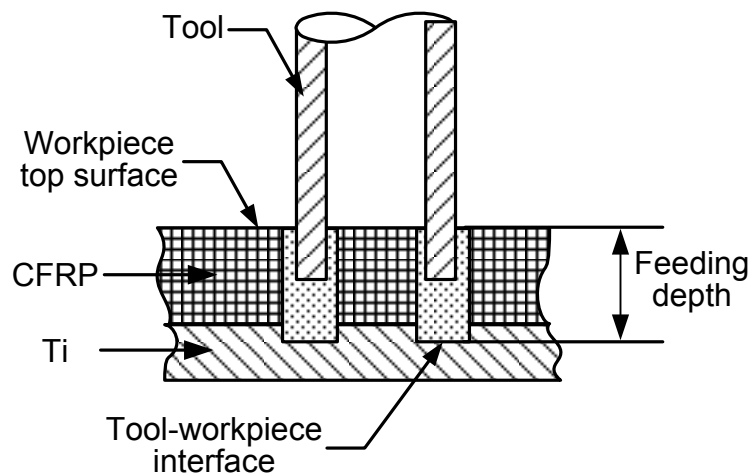


Figure 19.6 Illustration of feeding depth.

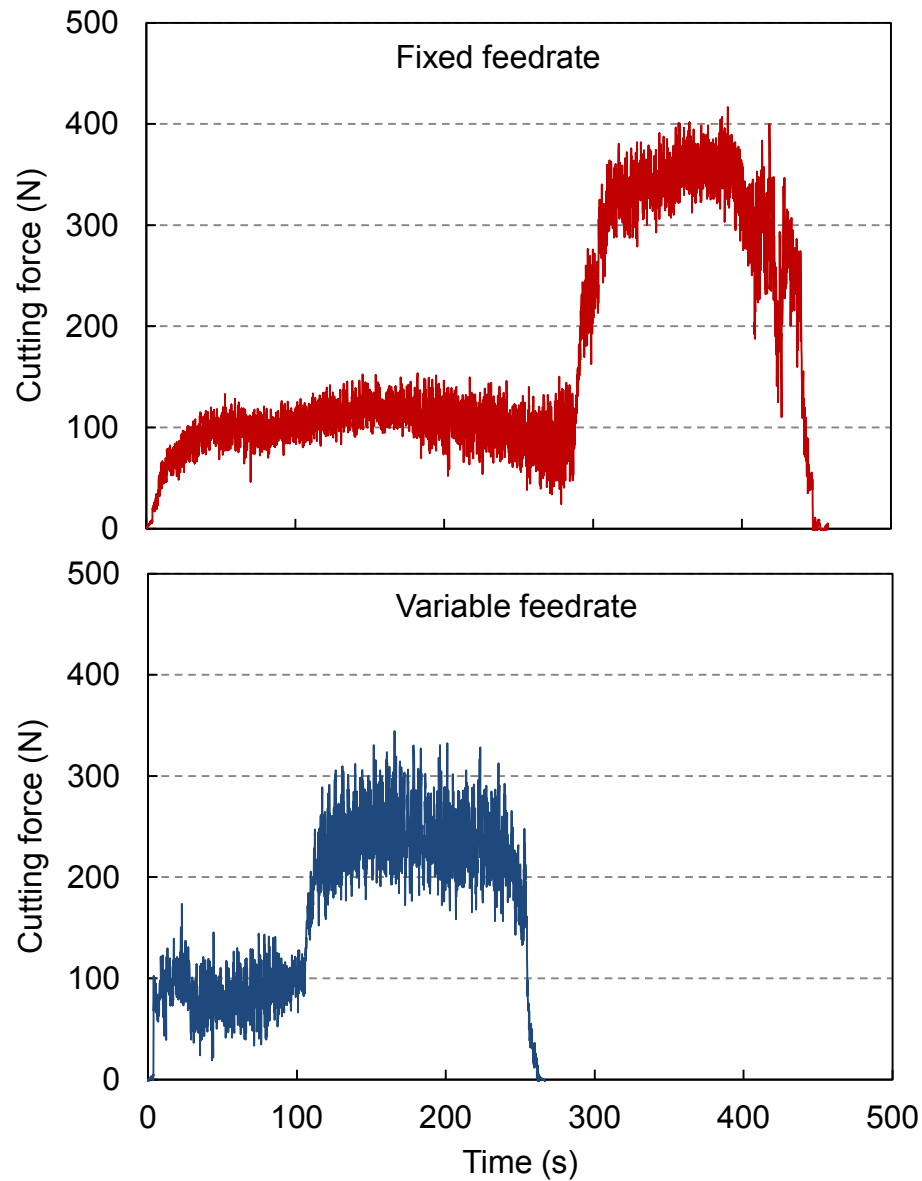


19.2.4 Measurement procedures

A dynamometer (Model 9272, Kistler Inc., Winterthur, Switzerland) was used to measure the cutting force (F_z) in the axial direction and torque. The electrical signals from the dynamometer were amplified by a charge amplifier (Model 5070A, Kistler Inc., Winterthur, Switzerland) and then transformed into digital signals by an A/D converter. After being processed by a signal conditioner, the digital signals were collected by a data acquisition card (PC-CARD-DAS16/16, Measurement Computing Corporation, Norton, MA, USA) on a computer with the help of Dynaware software (Type 2815A, Kistler Inc., Winterthur, Switzerland). The sampling rate was 20 Hz. The measured cutting force fluctuated with time within a certain range, as illustrated in Figure 19.7. The maximum cutting force of the cutting force-time curve was used to represent the cutting force for drilling of each hole. Similarly, the maximum torque of the torque-time curve was used to represent the torque for drilling of each hole. It is noted that the maximum cutting force and torque were obtained during drilling Ti for both types of feedrate.

In this paper, tool wear was defined as the weight loss of the cutting tool during each test. It was the difference between tool weights before and after a test. To remove any residuals left on the tool, the tool was cleaned using methanol and acetone and then was dried using a hand dryer before measurement. The weight of the tool was measured by a high-accuracy scale (Model APX-200, Denver Instrument, Denver, CO, USA).

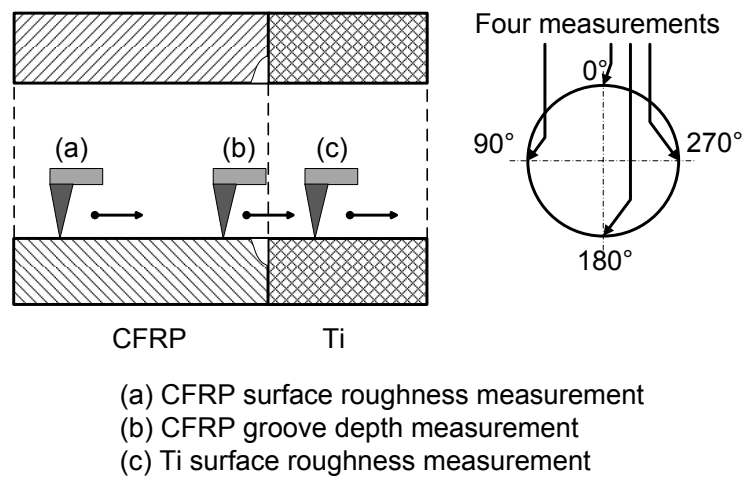
Figure 19.7 Typical cutting force-time curves using fixed and variable feedrate.



Surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan) was used to measure surface roughness of the hole surface and groove depth. Surface roughness was measured on the machined surfaces of CFRP and Ti along the axial direction of the hole. The surface roughness reported in this paper was Ra (average surface roughness). The test range and cut-off length of surface roughness measurement were set at 4 mm and 0.8 mm, respectively.

Groove depth (CFRP material near the interface between CFRP and Ti was overcut and a groove was formed) was measured on machined CFRP surface near the interface between CFRP and Ti. The details of measurement were illustrated in Figure 19.8. For both surface roughness and groove depth, four measurements were performed with 90° between two adjacent measurements. Each measurement was repeated twice. For each hole, there were eight values and the average of these eight values was used.

Figure 19.8 Surface roughness and groove depth measurements.

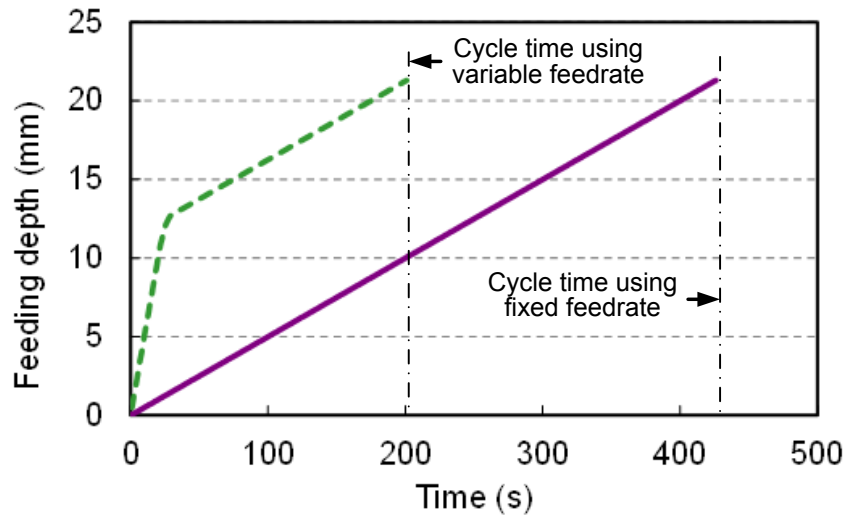


19.3 Results and discussion

19.3.1 Cycle time

Cycle time was the period of time it took to drill a hole through a CFRP/Ti stack. Figure 19.9 shows a comparison of cycle time between using fixed and variable feedrate. Compared with cycle time of 426 s using fixed feedrate, cycle time using variable feedrate was about 200 s.

Figure 19.9 Comparison of cycle time.



19.3.2 Cutting force

Figure 19.10 shows a comparison of cutting force between using fixed and variable feedrate at different levels of ultrasonic power. In Figure 19.10 (as well as Figure 19.11 – Figure 19.19), each data point is the average value for the four holes drilled under one test condition. Error bars represent the minimum and maximum values among the four holes. It can be seen from Figure 19.10 that cutting force using variable feedrate was lower than that using fixed feedrate at every level of ultrasonic power. The differences in cutting force between using fixed and variable feedrate were about the same when ultrasonic power was 0%, 20%, or 60%. When ultrasonic power was 40%, the largest difference occurred.

A comparison of cutting force between using fixed and variable feedrate at different levels of tool rotation speed is shown in Figure 19.11. Using fixed feedrate always led to higher cutting force than using variable feedrate at all levels of tool rotation speed. The differences in cuttings force between using fixed and variable feedrate were not the same at different levels of tool rotation speed. When tool rotation speed was 2000 rpm, the difference in cutting force

between using fixed variable feedrate was the largest. When tool rotation speed was 7000 rpm, the difference in cutting force was smallest.

Figure 19.10 Comparison of cutting force at different levels of ultrasonic power.
(Tool rotation speed = 4000 rpm)

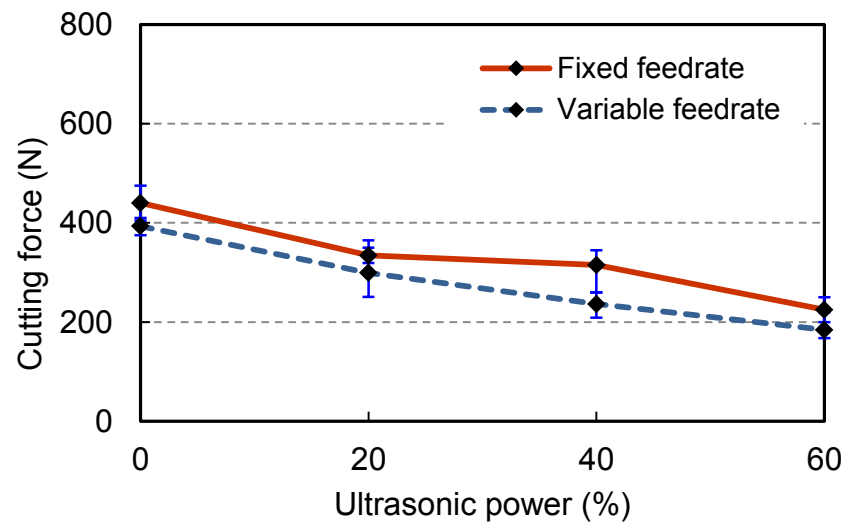
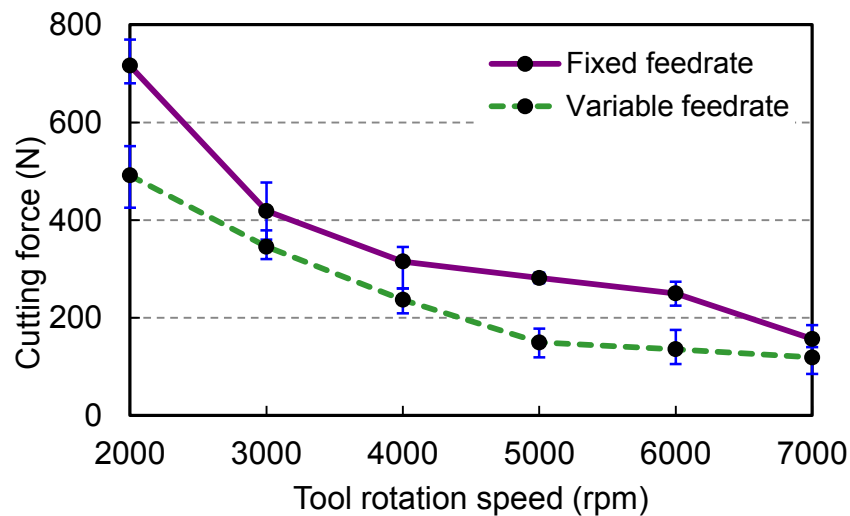


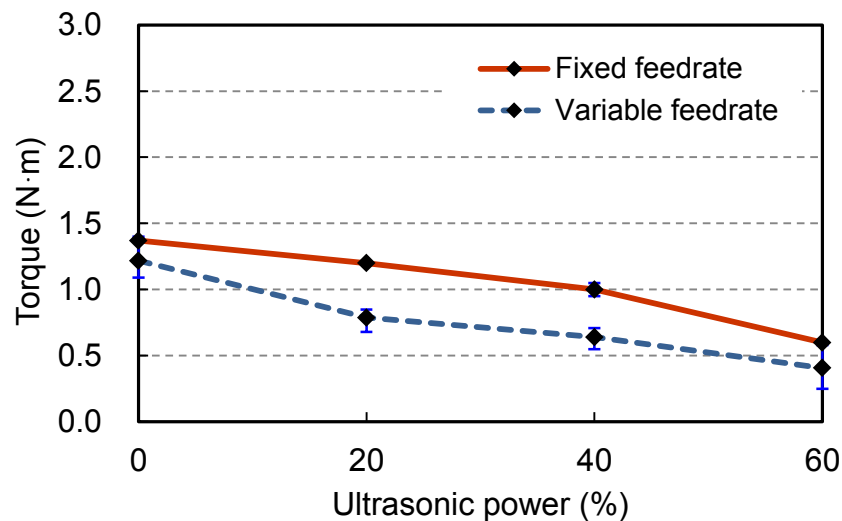
Figure 19.11 Comparison of cutting force at different levels of tool rotation speed.
(Ultrasonic power = 40%)



19.3.3 Torque

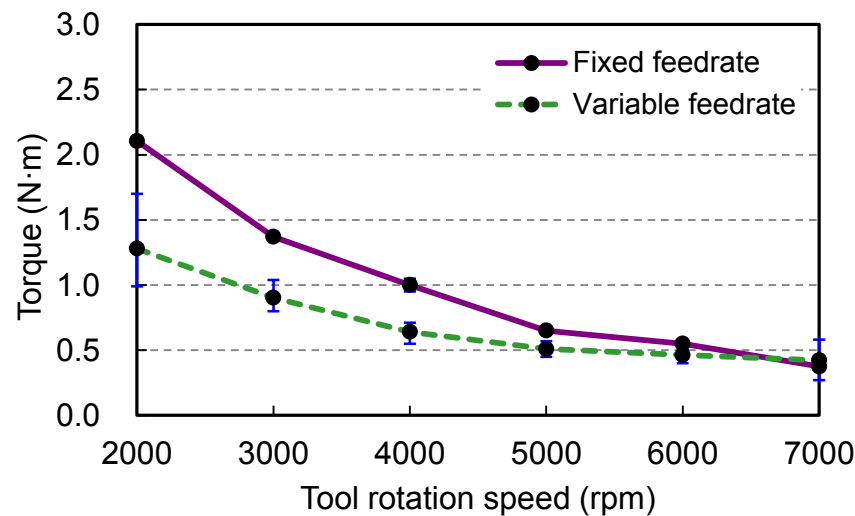
Figure 19.12 compares torque between using fixed and variable feedrate at different levels of ultrasonic power. Using fixed feedrate led to larger torque than using variable feedrate at all levels of ultrasonic power. Difference in torque between using fixed and variable feedrate reached the maximum when ultrasonic power was 20% and reached the minimum when ultrasonic power was 0%.

Figure 19.12 Comparison of torque at different levels of ultrasonic power.
(Tool rotation speed = 4000 rpm)



A comparison of torque between using fixed and variable at different levels of tool rotation speed is shown in Figure 19.13. At all levels of tool rotation speed, torque using variable feedrate was smaller than that using fixed feedrate except when the tool rotation speed was 7000 rpm where torque using variable feedrate was slightly larger than that using fixed feedrate. The difference in torque between using fixed and variable feedrate varied at different levels of tool rotation speed. The difference in torque reached the maximum when tool rotation speed was 2000 rpm, and reached the minimum when tool rotation speed was 7000 rpm.

**Figure 19.13 Comparison of torque at different levels of tool rotation speed.
(Ultrasonic power = 40%)**



19.3.4 Tool wear

Figure 19.14 compares tool wear (tool weight loss) between using fixed and variable feedrate at different levels of ultrasonic power. When ultrasonic power was 0%, 20%, or 40%, tool weight loss using fixed feedrate was larger than that using variable feedrate. However, when ultrasonic power was 60%, tool weight loss using fixed feedrate was smaller than that using variable feedrate. The difference in tool wear between using fixed and variable feedrate reached the maximum when ultrasonic power was 0% and reached the minimum when ultrasonic power was 40%.

A comparison of tool wear (tool weight loss) between using fixed and variable feedrate at different levels of tool rotation speed is shown in Figure 19.15. When tool rotation speed was 2000 or 3000 rpm, tool wear using variable feedrate was larger than that using fixed feedrate. In contrast, when tool rotation speed was 4000 or 7000 rpm, the difference in tool wear was negligible; and when tool rotation speed was 5000 or 6000 rpm, tool wear using variable feedrate

was less than that using fixed feedrate. The difference in tool wear between using fixed and variable feedrate, as well as tool wear using both fixed and variable feedrate, reached the maximum when tool rotation speed was 2000 rpm.

Figure 19.14 Comparison of tool wear at different levels of ultrasonic power.
(Tool rotation speed = 4000 rpm)

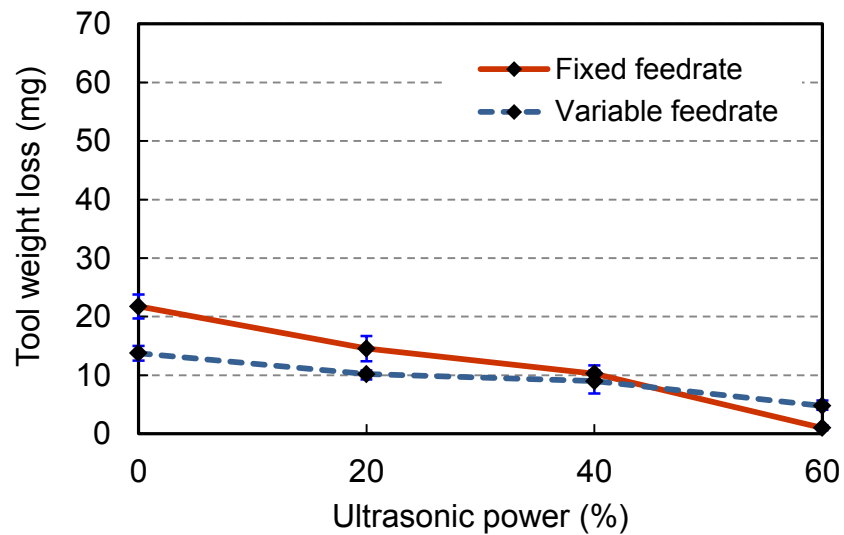
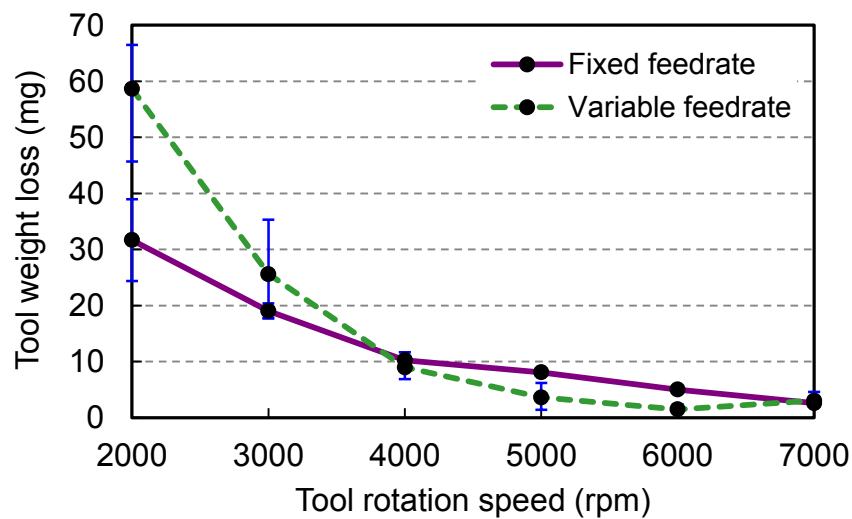


Figure 19.15 Comparison of tool wear at different levels of tool rotation speed.
(Ultrasonic power = 40%)



19.3.5 Surface roughness

Figure 19.16 (a) compares surface roughness on machined CFRP surface between using fixed and variable feedrate at different levels of ultrasonic power. Using variable feedrate led to higher surface roughness than using fixed feedrate at all levels of ultrasonic power. The difference in surface roughness between using fixed and variable feedrate was the smallest when ultrasonic power was 0% and largest when ultrasonic power was 60%.

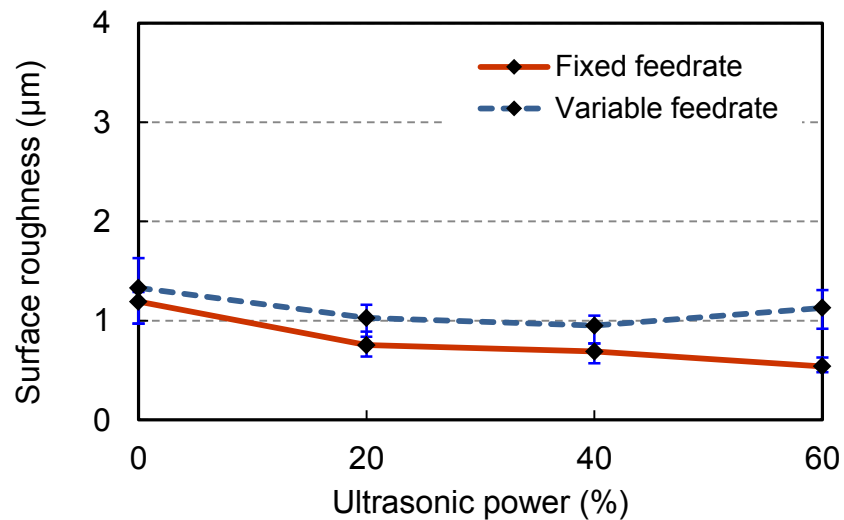
Figure 19.16 (b) compares surface roughness on machined Ti surface between using fixed and variable feedrate at different levels of ultrasonic power. Using fixed feedrate led to higher surface roughness than using variable feedrate when ultrasonic power was 0% or 20%, whereas, using fixed feedrate led to lower surface roughness than using variable feedrate when ultrasonic power was 60%. Surface roughness using fixed feedrate was similar to that using variable feedrate when ultrasonic power was 40%. Difference in surface roughness between using fixed and variable feedrate at 0% of ultrasonic power was larger than that at 20%, 40%, or 60% of ultrasonic power.

Figure 19.17 (a) compares of surface roughness on machined CFRP surface between using fixed and variable feedrate at different levels of tool rotation speed. Surface roughness using fixed feedrate was lower than that using variable feedrate at all levels of tool rotation speed. The difference in surface roughness between using fixed and variable feedrate was less than 1 μm . The maximum and minimum of difference were observed when tool rotation speed was 7000 and 4000 rpm, respectively.

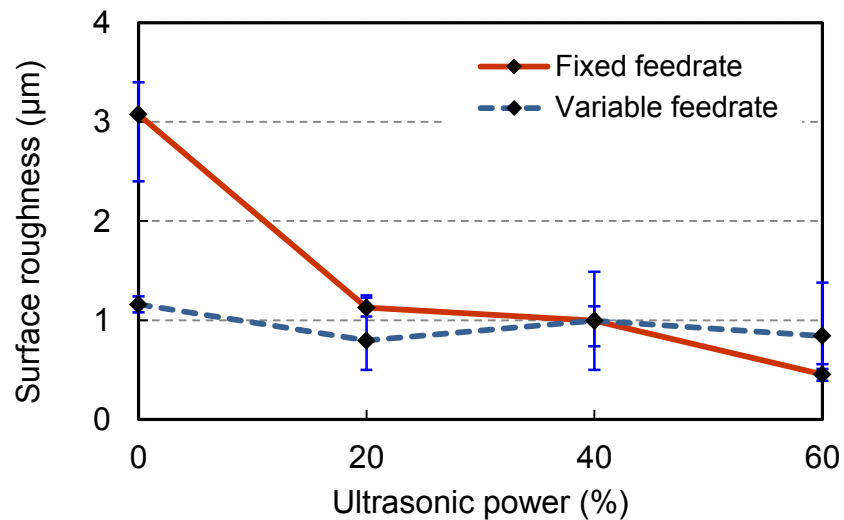
Figure 19.17 (b) compares surface roughness on machined Ti surface between using fixed and variable feedrate at different levels of tool rotation speed. When tool rotation speed was 2000 rpm, using variable feedrate led to remarkably higher surface roughness than using

fixed feedrate. When tool rotation speed was 3000 or 4000 rpm, surface roughness was similar using both types of feedrate. However, when tool rotation speed was from 5000 to 7000 rpm, using variable feedrate led to smaller surface roughness than using fixed feedrate.

Figure 19.16 Comparison of surface roughness at different levels of ultrasonic power.
(Tool rotation speed = 4000 rpm)

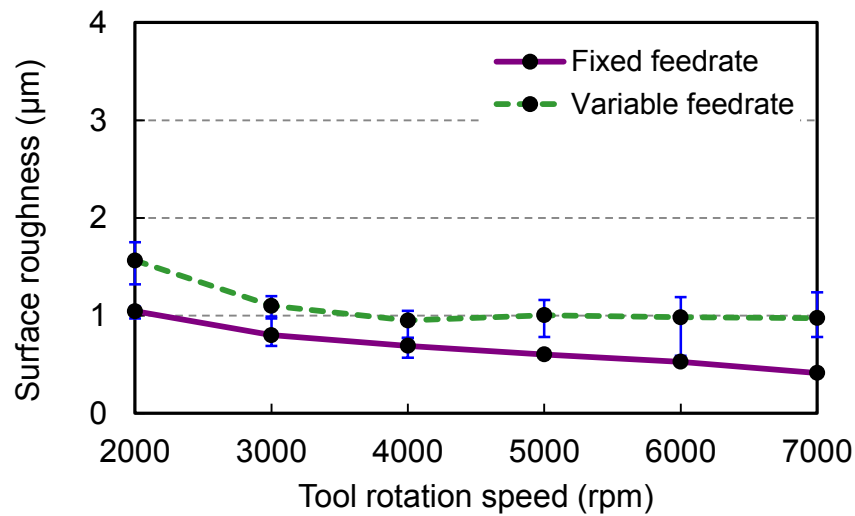


(a) Machined CFRP surface

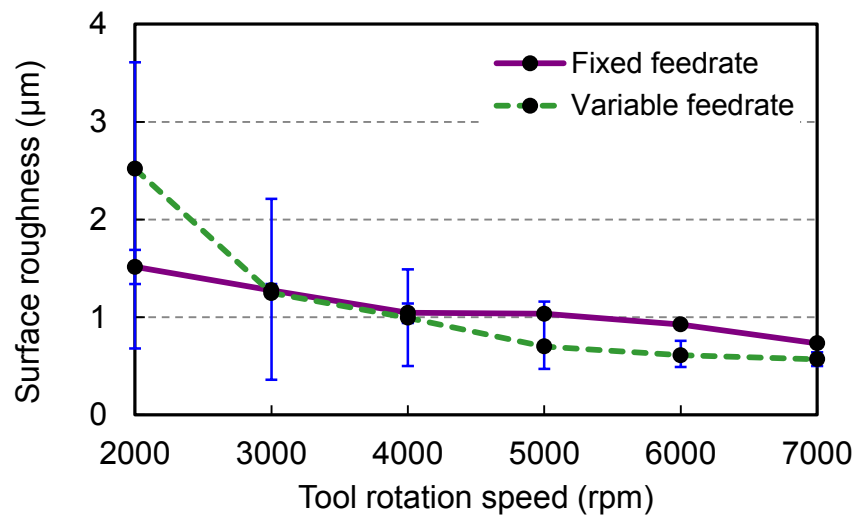


(b) Machined Ti surface

Figure 19.17 Comparison of surface roughness at different levels of tool rotation speed.
(Ultrasonic power = 40%)



(a) Machined CFRP surface



(b) Machined Ti surface

19.3.6 Groove depth

A comparison of groove depth between using fixed and variable feedrate at different levels of ultrasonic power is shown in Figure 19.18. At each level of ultrasonic power, groove

depth using variable feedrate was larger than that using fixed feedrate. The difference in groove depth between using fixed and variable feedrate decreased with the increase of ultrasonic power.

Figure 19.18 Comparison of groove depth at different levels of ultrasonic power.
(Tool rotation speed = 4000 rpm)

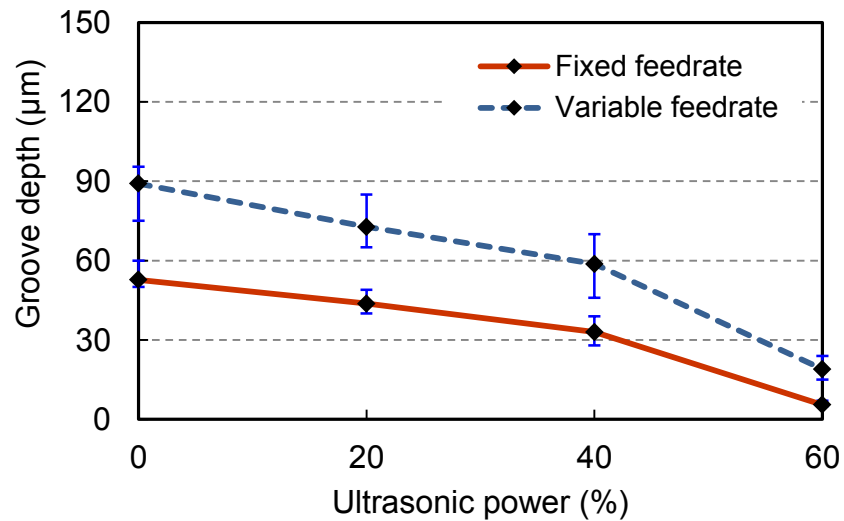


Figure 19.19 Comparison of groove depth at different levels of tool rotation speed.
(Ultrasonic power = 40%)

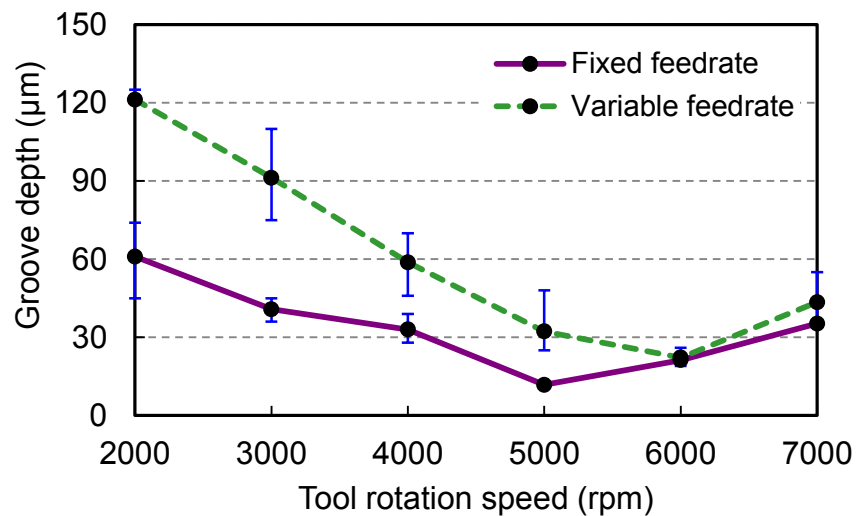


Figure 19.19 compares groove depth between using fixed and variable feedrate at different levels of tool rotation speed. At all levels of tool rotation speed, groove depth using variable feedrate was larger than that using fixed feedrate. The largest difference in groove depth between using fixed and variable feedrate was at 2000 rpm, and the smallest difference was obtained when tool rotation speed was 6000 rpm where the values of groove depth overlapped using both types of feedrate.

19.4 Conclusions

This paper reports a study on rotary ultrasonic machining (drilling) of CFRP/Ti stacks - using variable feedrate (higher feedrate for CFRP and lower feedrate for Ti). Comparisons between using fixed and variable feedrate at different levels of ultrasonic power and tool rotation speed have been made.

The following conclusions are drawn from this study:

- (a) Cycle time using variable feedrate was shorter than that using fixed feedrate.
- (b) Using variable feedrate led to a lower cutting force than using fixed feedrate at all levels of ultrasonic power and tool rotation speed. This was also true for torque at all levels of ultrasonic power and all levels of tool rotation speed except for 7000 rpm.
- (c) When ultrasonic power was low (0%, 20%, and 40%), using variable feedrate led to lower tool wear than using fixed feedrate. When tool rotation speed was 2000 rpm, using variable feedrate led to remarkably higher tool wear than using fixed feedrate.
- (d) Using variable feedrate always led to higher surface roughness on machined CFRP surface. When ultrasonic vibration was off, using variable feedrate resulted in remarkably lower surface roughness on machined Ti surface than using fixed feedrate. When tool rotation speed was 2000 rpm, using variable feedrate led to higher surface roughness on

machined Ti surface than using fixed feedrate.

- (e) Using variable feedrate led to larger groove depth at all levels of ultrasonic power than using fixed feedrate.

Acknowledgements

The work was supported by the National Science Foundation through award CMMI-0900462. The authors gratefully extend their acknowledgements to N.B.R. Diamond Tool Corp. for supplying the cutting tools.

References

[Boeing website] 787 Dreamliner Program Fact Sheet, available at: <http://www.boeing.com/commercial/787family/programfacts.html>, Accessed on June 24, 2012.

[Brinksmeier and Janssen, 2002] Brinksmeier E., and Janssen R., 2002, Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys, CIRP Annals - Manufacturing Technology, 51(1), pp. 87-90.

[Brochure, 2009] Brochure, 2009, The Global Aerospace Market Trends and Forecast 2009-2028, available at: http://www.researchandmarkets.com/reports/1086286/the_global_aerospace_market_trends_and_forecast, Accessed on June 24, 2012.

[Chung, 2010] Chung D.D.L., 2010, Composite Materials Science and Applications, Second edition, Springer-Verlag London Ltd., London, UK.

[Churi et al., 2005] Churi N.J., Li Z.C., Pei Z.J., and Treadwell C., 2005, Rotary ultrasonic machining of titanium alloy: a feasibility study, Proceedings of the 2005 ASME

International Mechanical Engineering Congress and Exposition (IMECE 2005), Orlando, FL, USA, November 5-11, pp. 885-892.

[Churi et al., 2006] Churi N.J., Pei Z.J., and Treadwell C., 2006, Rotary ultrasonic machining of titanium alloy: effects of machining variables, *Machining Science and Technology*, 10(3), pp. 301-321.

[Churi et al., 2007a] Churi N.J., Pei Z.J., and Treadwell C., 2007a, Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables, *International Journal of Precision Technology*, 1(1), pp. 85-96.

[Churi et al., 2007b] Churi N.J., Pei Z.J., and Treadwell C., 2007b, Wheel wear mechanisms in rotary ultrasonic machining of titanium, *Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition (IMECE 2007)*, Seattle, WA, USA, November 11-15, pp. 399-407.

[Colligan, 1994] Colligan K., 1994, New tool drills both titanium and carbon composites, *American Machinist*, (10), pp.56-58.

[Cong et al., 2011a] Cong W.L., Pei Z.J., Feng Q., Deines T.W., and Treadwell C., 2011, Experimental study on cutting temperature in rotary ultrasonic machining, *Proceedings of NAMRI/SME*, 39, pp. 369-376.

[Cong et al., 2011b] Cong W.L., Pei Z.J., Deines T.W., and Treadwell C., 2011, Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions, *Journal of Reinforced Plastics and Composites*, 30(10), pp. 899-906.

[Cong et al., 2011c] Cong W.L., Feng Q., Pei Z.J., Deines T.W., and Treadwell C., 2011, Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables, *Proceedings of the ASME 2011 International Manufacturing*

Science and Engineering Conference (MSEC), Corvallis, OR, USA, June 13-17, MSEC2011-50116.

[Cong et al., 2012a] Cong W.L., Pei Z.J., Feng Q., Deines T.W., and Treadwell C., 2012, Rotary ultrasonic machining of CFRP: a comparison with twist drilling, *Journal of Reinforced Plastics and Composite*, 31(5), pp. 313-321.

[Cong et al., 2012b] Cong W.L., Pei Z.J., Feng Q., Deines T.W., and Treadwell C., 2012, Rotary ultrasonic machining of carbon fiber reinforced plastic composites: using cutting fluid versus cold air as coolant, *Journal of Composite Materials*, 46(14), pp. 1747-1753.

[Cookson, 2009] Cookson I., 2009, Sector outperforms: 2008 M&A activity matches prior-year record, *Aerospace Components*, (February), pp.1-5

[Davim and Reis, 2003] Davim J.P., and Reis P., 2003, Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, *Materials and Design*, 24(5), pp. 315-324.

[Denkena et al., 2008] Denkena B., Boehnke D., Dege J.H., 2008, Helical milling of CFRP-titanium layer compounds, *CIRP Journal of manufacturing Science and Technology*, 1(2), pp. 64-69.

[Garrick, 2007] Garrick R., 2007, Drilling advanced aircraft structures with PCD (Polycrystalline Diamond) Drills, *AeroTech Congress & Exhibition*, Los Angeles, CA, USA, September 18-20.

[Guu et al., 2001] Guu Y.H., Hocheng H., Tai N.H., and Liu S.Y., 2001, Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites, *Journal of Materials Science*, 36(8), pp. 2037-2043.

[Kim and Lee, 2005] Kim G.W., and Lee K.Y., 2005, Critical thrust force at propagation of delamination zone due to drilling of FRP/metallic strips, *Composite Structures*, 69(2), pp. 137-141.

[Kim and Ramulu, 2004] Kim D., and Ramulu M., 2004, Drilling process optimization for graphite/bismaleimide-titanium alloy stacks, *Composite Structures*, 63(1), pp. 101-114.

[Kim and Ramulu, 2005] Kim D., and Ramulu M., 2005, Cutting and drilling characteristics of hybrid titanium composite laminate (HTCL), 37th Proceedings of materials and processing technologies for revolutionary applications fall technical conference, Seattle, WA, USA, October 31 - November 3, pp. 1-8.

[Kim and Ramulu, 2005] Kim D., and Ramulu M., 2005, Study on the drilling of Titanium/Graphite hybrid composites, ASME International Mechanical Engineering Congress and Exposition, Orlando, FL, USA, November 5-11, pp. 99-106.

[Kim and Ramulu, 2005] Kim D., and Ramulu M., 2005, Study on the drilling of titanium/Graphite hybrid composites, *Journal of Engineering Materials and Technology*, 129(3), pp. 390-396.

[Kim et al. 2001] Kim D., Ramulu M., Garbini J., 2001, Hole quality in drilling of Graphite/Bismaleimide-Titanium stacks, 33rd International SAMPE Technical Conference, Seattle, WA, USA, November 5-8, pp. 1315-1326.

[Kim et al., 2005] Kim D., Ramulu M., and Pedersen W., 2005, Machinability of titanium/graphite hybrid composites in drilling, *Transactions of NAMRI/SME*, 33, pp. 445-452.

[Lambert, 1987] Lambert B.K., 1987, Cutting and drilling of composite materials, *The Carbide and Tool Journal*, 19(5), pp. 31-34.

[Li et al., 2007] Li Z.C., Pei Z.J., Sisco T., Micale A.C., and Treadwell C., 2007, Experimental study on rotary ultrasonic machining of graphite/epoxy panel, ASPE Spring Topical Meeting on Vibration Assisted Machining Technology, Chapel Hill, NC, USA, April 16-17, pp. 52-57.

[Mallick, 1997] Mallick P.K., 1997, Composite Engineering Handbook, Marcel Dekker Inc., New York, NY, USA.

[Mangalgi, 1999] Mangalgi P.D., 1999, Composite materials for aerospace application, Bulletin of Material Science, 22(3), pp. 657-664.

[Margolis 2006] Margolis D., Stacking the odds, Cutting Tool Engineering, (8), pp. 74-80.

[Ramulu et al., 2001] Ramulu M., Branson T., Kim D., 2001, A study on the drilling of composite and titanium stacks, Composite Structures, 54(10), pp. 67-77.

[Sadat, 1995] Sadat A.B., 1995, Delamination and other types of damage of graphite/epoxy composite caused by machining, American Society of Mechanical Engineers, Applied Mechanics Division, 208, pp. 41-52.

[Schwartz, 1992] Schwartz M.M., 1992, Composite Materials Handbook, Second edition, McGraw-Hill, Columbus, OH, USA.

[Shyha et al., 2010] Shyha I.S., Soo S.L., Aspinwall D.K., Bradley S., Dawson S., and Pretorius C.J., 2010, Drilling of titanium/CFRP/Aluminum stacks, Key Engineering Materials, 447-448, pp. 624-633.

[Weiss, 1989] Weiss R.A., 1989, Portable air feed peck drilling of graphite composite, titanium and other materials in dissimilar combinations, FASTEC '89, Arlington, Texas, USA, October 4-6.

[Yagishita, 2008] Yagishita H., Comparing drilling and circular milling for hole making in bi-layer composite materials consisting of carbon fiber reinforced plastic (CFRP) laminates and titanium alloys, Transactions of NAMRI/SME, 36, pp. 17-24.

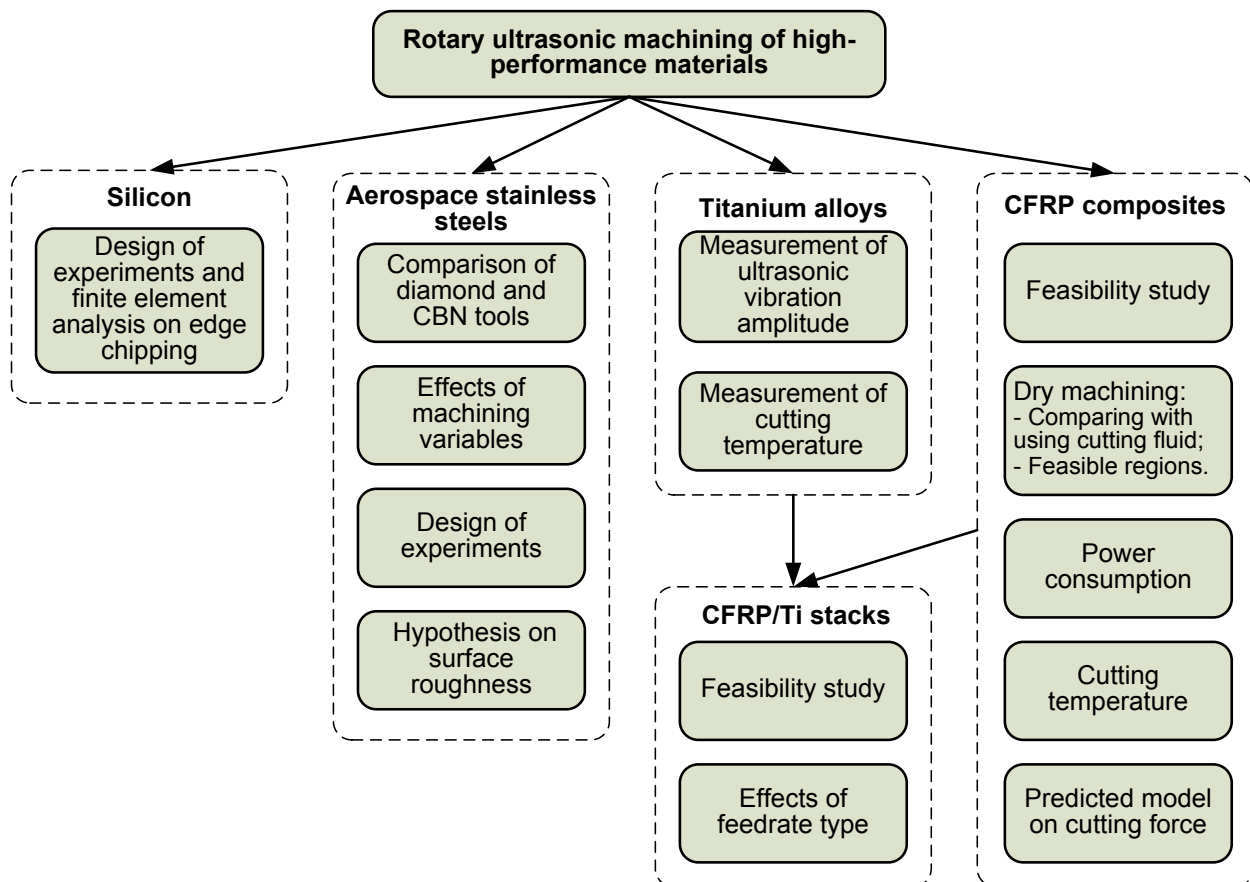
[Zitoune et al., 2010] Zitoune R., Krishnaraj V., Collombet F., 2010, Study of drilling of composite material and aluminium stack, Composite Structures, 92(5), pp. 1246-1255.

Chapter 20 - Conclusions and contributions

20.1 Conclusions

In this dissertation, high-performance materials (including silicon, aerospace stainless steels, titanium alloys, and CFRP composites) had been drilled by rotary ultrasonic machining. The studies presented in this dissertation are shown in Figure 20.1.

Figure 20.1 Studies of this dissertation.



The conclusions drawn from this dissertation are:

- (1). When RUM of silicon, higher tool rotation speed, higher ultrasonic power, and lower feedrate led to smaller edge chipping thickness and lower cutting force. Larger edge chipping was almost always accompanied by higher cutting force.
- (2). When RUM of aerospace stainless steels, cutting force and torque decreased as spindle speed increased or feedrate decreased. Surface roughness increased as spindle speed or feedrate increased. Surface roughness was lowest when ultrasonic power was 30%. Surface roughness at the entrance location was almost always lower than that at the exit location. The CBN tool had more severe wear, larger cutting force, larger torque, and lower surface roughness than the diamond tool under the experimental conditions used in this study.
- (3). An ultrasonic amplitude measurement method and a cutting temperature measurement method were developed in RUM of titanium alloys. The vibration amplitude during RUM machining was different when using tools that were different in weight, length, or diameter. Excluding cutting tool, ultrasonic power was the only input variable significantly affecting vibration amplitude. Vibration amplitude showed no significant variations with changes in workpiece material, tool rotation speed, and feedrate. Cutting temperature with ultrasonic vibration was lower than that without ultrasonic vibration. When ultrasonic vibration was on, cutting temperature increased as ultrasonic power increased. Lower feedrate led to higher cutting temperature. As tool rotation speed increased, cutting temperature decreased to a value and then increased. Cutting temperatures with outer coolant were much lower than those without outer coolant.

- (4). RUM of CFRP composites led to lower cutting force, torque, surface roughness, tool wear than twist drilling. The holes machined by RUM did not show any delamination. RUM of CFRP composites could be accomplished using cold air as coolant, with some limitations. As ultrasonic power increased or tool rotation speed decreased, power consumption of ultrasonic power supply increased slightly, power consumption of spindle motor decreased dramatically, power consumption of coolant pump and air compressor kept unchanged, and power consumption of the entire RUM system increased slightly. As feedrate decreased, power consumptions of ultrasonic power supply, spindle motor, and coolant pump decreased dramatically, power consumption of air compressor kept the same, and power consumption of the entire RUM system increased remarkably.
- (5). By developing the mechanistic predictive model for cutting force in RUM of CFRP composites, it could be concluded that cutting force decreased remarkably as feedrate decreased, tool rotation speed increased, or abrasive size increased. Cutting force decreased slightly with increase of ultrasonic amplitude or decrease of abrasive concentration. The relationship between cutting force and feedrate under different levels of tool rotation speed was linear. However, the relationship between cutting force and other input variables were nonlinear.
- (6). Compared with other reported methods for drilling of CFRP/Ti stacks, RUM resulted in lower cutting force and CFRP surface roughness, smaller groove depth and hole size variation, and longer tool life. There was no obvious Ti exit burr and CFRP entrance delamination when using RUM to drill CFRP/Ti stacks. Ti surface roughness in drilling of CFRP/Ti stacks using RUM was about the same as those using other methods. To increase the drilling efficiency (decrease the drilling cycle time), variable feedrate was

used in RUM of CFRP/Ti stacks. Using variable feedrate led to a lower cutting force, lower torque, higher surface roughness on machined surface, and larger groove depth than using fixed feedrate.

20.2 Contributions of this dissertation

The major contributions of this dissertation are:

- (1). This research, for the first time, presented a study on RUM of silicon. Investigations on edge chipping were conducted by experiments and finite element analysis.
- (2). This research, for the first time, presented a study on RUM of aerospace stainless steels. Investigations on cutting force, torque, surface roughness, and tool wear were conducted by experiments and finite element analysis.
- (3). This research, for the first time, developed an ultrasonic vibration amplitude measurement method and a cutting temperature measurement method in RUM (using titanium alloy as the workpiece material).
- (4). This research, for the first time, studied RUM of CFRP composites using cold air as coolant. Investigations on cutting force, torque, surface roughness, delamination, tool wear, cutting temperature, power consumption, and feasible regions were conducted by experiments.
- (5). This research, for the first time, developed a cutting force model on RUM of CFRP materials. The effects of ultrasonic vibration amplitude, tool rotation speed, feedrate, abrasive size, and abrasive concentration on cutting force have been investigated. Experimental investigations have been conducted to verify the model.

- (6). This research, for the first time, studied RUM of CFRP/Ti stacks. Investigations on cutting force, torque, surface roughness, CFRP groove depth, Ti exit burr, CFRP entrance delamination, hole size variance, and tool life were conducted by experiments.

Appendix A - Publications during Ph.D. study

Journals and transactions

1. Cong, W.L., Zou, X.T., Deines, T.W., Wu, N., Wang, X.W., Pei, Z.J., 2012, "Rotary ultrasonic machining of CFRP composites: an experimental study on cutting temperature," Journal of Reinforced Plastics and Composite, Vol. 31, No. 22, pp. 1516-1525.
2. Cong, W.L., Pei, Z.J., Deines, T.W., Srivastava, A., Riley, L., and Treadwell, C., 2012, "Rotary ultrasonic machining of CFRP composites: a study on power consumption," Ultrasonics, Vol. 52, No. 8, pp. 1030-1037.
3. Cong, W.L., Pei, Z.J., Feng, Q., Deines, T.W., and Treadwell, C., 2012, "Rotary ultrasonic machining of CFRP: a comparison with twist drilling," Journal of Reinforced Plastics and Composite, Vol. 31, No. 5, pp. 313-321.
4. Cong, W.L., Feng, Q., Pei, Z.J., Deines, T.W., and Treadwell, C., 2012, "Edge chipping in rotary ultrasonic machining of silicon," International Journal of Manufacturing Research, Vol. 7, No. 3, pp. 311-329.
5. Cong, W.L., Feng, Q., Pei, Z.J., Deines, T.W., and Treadwell, C., 2012, "Rotary ultrasonic machining of carbon fiber reinforced plastic composites: using cutting fluid versus cold air as coolant," Journal of Composite Materials, Vol. 46, No. 14, pp. 1745-1753.
6. Cong, W.L., Pei, Z.J., Deines, T.W., and Treadwell, C., 2011, "Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions," Journal of Reinforced Plastics and Composites, Vol. 30, No. 10, pp. 899-906.
7. Cong, W.L., Pei, Z.J., Mohan1ty, N., Van Vleet, E., and Treadwell, C., 2011, "Vibration amplitude in rotary ultrasonic machining: a novel measurement method and effects of process variables," Journal of Manufacturing Science and Engineering, Vol. 133, No. 3, pp. 034501-1 – 034501-6.
8. Cong, W.L., Pei, Z.J., Zhang, P.F., Qin, N., Deines, T.W., and Lin, B., 2011, "Ultrasonic-vibration-assisted pelleting of switchgrass: effects of ultrasonic vibration," Transactions of Tianjin University, Vol. 17, No. 5, pp. 313-319.

9. Cong, W.L., Pei, Z.J., Deines, T.W., Wang, Q.G., and Treadwell, C., 2010, "Rotary ultrasonic machining of stainless steels: empirical study of machining variables," *International Journal of Manufacturing Research*, Vol. 5, No. 3, pp. 370-386.
10. Cong, W.L., Zhang, P.F., and Pei, Z.J., 2009, "Experimental investigations on material removal rate and surface roughness in lapping of substrate wafers: a literature review," *Key Engineering Materials*, Vol. 404, pp. 23-31.
11. Cong, W.L., Pei, Z.J., Churi, N.J., and Wang, Q.G., 2009, "Rotary ultrasonic machining of stainless steel: design of experiments," *Transactions of the North American Manufacturing Research Institution of SME*, Vol. 37, pp. 261-268.
12. Zou, X.T., Cong, W.L., Wu, N., Tian, Y., Wang, H.F., Pei, Z.J., and Wang, X.W., 2012, "Cutting temperature in rotary ultrasonic machining of titanium: experimental study using novel Fabry-Perot fiber optic sensors," accepted to appear in *International Journal of Manufacturing Research*.
13. Tang, Y.J., Zhang, P.F., Liu, D.F., Pei, Z.J., and Cong, W.L., 2012, "Ultrasonic vibration-assisted pelleting of cellulosic biomass for biofuel manufacturing: a study on pellet cracks," *Journal of Manufacturing Science and Engineering*, Vol. 134, No. 5, pp. 051016-1 – 051016-8
14. Ahmed, Y., Cong, W.L., Stanco, M.R., Xu, Z.G., Pei, Z.J., Treadwell, C., Zhu, Y.L., Li, Z.C., "Rotary ultrasonic machining of alumina dental ceramics: a preliminary experimental study on surface and subsurface damages," *Journal of Journal of Manufacturing Science and Engineering*, Vol. 134, No. 6, pp. 064501-1 – 064501-5.
15. Feng, Q., Cong, W.L., Pei, Z.J., and Ren, C.Z., 2012, "Rotary ultrasonic machining of carbon fiber reinforced polymer: feasibility study," *Machining Science and Technology*, Vol. 16, No. 3, pp. 380-398.
16. Liu, D.F., Cong, W.L., Pei, Z.J., and Tang, Y.J., 2012, "A cutting force model for rotary ultrasonic machining of brittle materials," *International Journal of Machine Tools and Manufacture*, Vol. 52, No. 1, pp. 77-84.
17. Liu, D.F., Tang, Y.J., and Cong, W.L., 2012, "A review of mechanical drilling for composite

- laminates,” *Composite Structures*, Vol. 94, No. 4, pp. 1265-1279.
18. Wu, J.Q., Cong, W.L., Williams, R.E., and Pei, Z.J., 2011, “Dynamic process modeling for rotary ultrasonic machining of alumina,” *Journal of Manufacturing Science and Engineering*, Vol. 133, No. 4, pp. 041012-1– 041012-5.
 19. Zhang, P.F., Pei, Z.J., Wang, D.H., Wu, X.R., Cong, W.L., Zhang, M., and Deines, T.W., 2011, “Ultrasonic vibration-assisted pelleting of cellulosic biomass for biofuel manufacturing,” *Journal of Manufacturing Science and Engineering*, Vol. 133, No. 1, pp. 011012-1 – 011012-7.
 20. Feng, Q., Cong, W.L., Zhang, M., Pei, Z.J., and Ren, C.Z., 2011, “An experimental study on charring of cellulosic biomass in ultrasonic vibration-assisted pelleting,” *International Journal of Manufacturing Research*, Vol. 6, No. 1, pp. 77-86.
 21. Wang, Q.G., Cong, W.L., Pei, Z.J., Gao, H., and Kang, R.K., 2009, “Rotary ultrasonic machining of potassium dihydrogen phosphate (KDP) crystal: an experimental investigation on surface roughness,” *Journal of Manufacturing Processes*, Vol. 11, No. 2, pp. 66-73.

Proceedings

22. Cong, W.L., Feng, F., Pei, Z.J., Deines, T.W., and Treadwell, C., 2011, "Experimental study on cutting temperature in rotary ultrasonic machining," Proceedings of NAMRI/SME, Vol. 39, pp. 369-376, Corvallis, OR, USA, June 13-17.
23. Cong, W.L., Feng, F., Pei, Z.J., Deines, T.W., and Treadwell, C., 2011, "Dry machining of carbon fiber reinforced plastic composite by rotary ultrasonic machining: effects of machining variables," Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference (MSEC 2011), Corvallis, OR, USA, June 13-17.
24. Cong, W.L., and Pei, Z.J., 2011, "Survey of courses on renewable energy manufacturing at American universities," Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference (MSEC 2011), Corvallis, OR, USA June 13-17.
25. Cong, W.L., Deines, T.W., Feng, Q., Zhang, P.F., Qin, N., and Pei, Z.J., 2011, "Fundamental Research on Titanium drilling with rotary ultrasonic machining: 2010 progress report," CD-ROM Proceedings of 2011 NSF CMMI Research and Innovation Conference; Atlanta, GA, USA, January 4-7.
26. Cong, W.L., Feng, Q., and Pei, Z.J., 2010, "Drilling of silicon based solar panels: a review," Proceedings of the ASME 2010 International Manufacturing Science and Engineering Conference (MSEC 2010), Erie, PA, USA, October 12-15.
27. Cong, W.L., Feng, Q., Pei, Z.J., and Treadwell, C., 2010, "Comparison of superabrasive tools in rotary ultrasonic machining of stainless steel," Proceedings of the ASME 2010 International Manufacturing Science and Engineering Conference (MSEC 2010), Erie, PA, USA, October 12-15.
28. Cong, W.L., Pei, Z.J., and Zhang, P.F., 2009, "Experimental investigations on flatness and subsurface damage in lapping of substrate wafers: a literature review," Proceedings of 2009 International Manufacturing Science and Engineering Conference (MSEC 2009), West Lafayette, IN, USA, October 4-7.
29. Cong, W.L., Pei, Z.J., Van Vleet, E., and Wang, Q.G., 2009, "Surface roughness in rotary ultrasonic machining of stainless steels," Proceedings of the IIE Annual Conference and

Expo 2009 – Innovations Revealed, Miami, FL, USA, May 30 - June 3.

30. Cong, W.L., and Pei, Z.J., 2008, “Dry machining using vortex-tube generated cold air as coolant: a literature review,” Proceedings of the ASME 2008 International Manufacturing Science & Engineering Conference (MSEC 2008), Evanston, IL, USA, October 7-10.
31. Qin, N., Pei, Z.J., Cong, W.L., Treadwell, C., and Guo, D.M., 2011, “Ultrasonic vibration-assisted grinding of brittle materials: a mechanistic model for cutting force,” Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference (MSEC 2011), Corvallis, OR, USA, June 13-17.
32. Zhang, P.F., Zhang, M., Song, X.X., Zhang, Q., Cong, W.L., Qin, N., Pei, Z.J., Deines, T.W., and Wang, D.H., 2011, “Ultrasonic vibration-assisted pelleting of cellulosic biomass for biofuel manufacturing,” CD-ROM Proceedings of 2011 NSF CMMI Research and Innovation Conference, Atlanta, GA, USA, January 4-7.
33. Qin, N., Cong, W.L., Zhang, P.F., and Pei, Z.J., 2011, “Fundamental research on silicon wafer fine grinding: 2010 progress report,” CD-ROM Proceedings of 2011 NSF CMMI Research and Innovation Conference, Atlanta, GA, USA, January 4-7.
34. Zou, X.T., Guthy, C., Cong, W.L., Pei, Z.J., and Wang, X.W., 2011, “Cutting temperature distribution in rotary ultrasonic machining of titanium alloy: Finite element analysis and experimental design using an optical temperature sensor array,” CD-ROM Proceedings of 2011 NSF CMMI Research and Innovation Conference, Atlanta, GA, USA, January 4-7.
35. Feng, Q., Cong, W.L., Zhang, M., Pei, Z.J., and Ren, C.Z., 2010, “An experimental study on temperature in ultrasonic vibration-assisted pelleting of cellulosic biomass,” Proceedings of the ASME 2010 International Manufacturing Science and Engineering Conference (MSEC 2010), Erie, PA, USA, October 12-15.
36. Qin, N., Pei, Z.J., Cong, W.L., and Guo, D.M., 2010, “Effects of tool design on edge chipping in ultrasonic-vibration-assisted grinding,” Proceedings of the ASME 2010 International Manufacturing Science and Engineering Conference (MSEC 2010), Erie, PA, USA, October 12-15.
37. Zhang, P.F., Deines, T.W., Cong, W.L., Qin, N., Pei, Z.J., and Nottingham, D., 2010, “Ultrasonic vibration-assisted pelleting of switchgrass: effects of moisture content on pellet density, spring-back, and durability,” Proceedings of the 20th International Conference on

Flexible Automation and Intelligent Manufacturing (FAIM 2010), California State University, CA, USA, July 12-14.

38. Zhang, M., Song, X.X., Deines, T.W., Zhang, P.F., Zhang, Q., Cong, W.L., Qin, N., and Pei, Z.J., 2010, "Ultrasonic-vibration-assisted pelleting of switchgrass: effects of binder material," Proceedings of the IIE Annual Conference and Expo 2010, Cancun, Mexico, June 5-9.
39. Qin, N., Pei, Z.J., Cong, W.L., and Guo, D.M., 2010, "UVAG of brittle materials: DOE with a cutting force model," Proceedings of the IIE Annual Conference and Expo 2010, Cancun, Mexico, June 5-9.
40. Li, Z.C., Stanco, M.R., Cong, W.L., Pei, Z.J., Xu, Z.G., and Treadwell, C., 2010, "Rotary ultrasonic machining of dental ceramics: a preliminary study on subsurface cracks," Proceedings of the ASME 2010 Design of Medical Devices Conference (DMD 2010), Minneapolis, MN, USA, April 13-15.
41. Wu, J.Q., Cong, W.L., Williams, R.E., and Pei, Z.J., 2009, "Stochastic modeling and analysis of rotary ultrasonic machining," Proceedings of the ASME 2009 International Manufacturing Science & Engineering Conference (MSEC 2009), West Lafayette, IN, USA, October 4-7.
42. Zhang, P.F., Li, Z.C., Cong, W.L., and Pei, Z.J., 2009, "Fundamental research on silicon wafer fine grinding: 2008 progress report," CD-ROM Proceedings of 2009 NSF Civil, Mechanical and Manufacturing Innovation Grantees and Research Conference, Honolulu, HI, USA, June 22-25.

Submitted papers

43. Cong, W.L., Pei, Z.J., and Zhang, C.L., “Rotary ultrasonic machining of CFRP: a mechanistic predictive model for cutting force”, submitted to Ultrasonics.
44. Cong, W.L., Pei, Z.J., Deines, T.W., Liu, D.F., and Treadwell C., “Rotary ultrasonic machining of CFRP/Ti stacks: a feasibility study”, submitted to Journal of Manufacturing Science and Engineering.
45. Cong, W.L., Pei, Z.J., Deines, T.W., Liu, D.F., and Treadwell C., “Rotary ultrasonic machining of CFRP/Ti stacks: using variable feedrate”, submitted to Composite Part B.
46. Cong, W.L., Pei, Z.J., Deines, T.W., Zhang, P.F., and Treadwell, C., “Surface roughness in rotary ultrasonic machining: hypotheses and their testing via experiments and simulations”, submitted to International Journal of Manufacturing Research.
47. Tang, Y.J., Cong, W.L., Zhang, P.F., Liu D.F., and Pei, Z.J., “Ultrasonic vibration-assisted pelleting for cellulosic biofuels manufacturing: a study on in-pellet temperatures”, submitted to Renewable Energy.

Posters

48. Cong, W.L., Zhang, P.F., Qin, N., Zhang, M., Song, X.X., Zhang, Q., Nottingham, N., Clark, R., Deines, T.W., Pei, Z.J., and Wang, D.H., 2009, "Ultrasonic vibration-assisted pelleting of cellulosic biomass for biofuel manufacturing," Poster presentation at the ASME 2009 International Manufacturing Science and Engineering Conference (MSEC), MSEC2009-84432, West Lafayette, IN, USA, October 4-7.
49. Zhang, P.F., Feng, Q., Zinke, E., Cong, W.L., Zhang, M., Song, X.X., Zhang, Q., Deines, T.W., Pei, Z.J., and Wang, D.H., 2010, "Ultrasonic vibration-assisted pelleting of cellulosic biomass for bioethanol manufacturing," Poster presentation at the ASME 2010 International Manufacturing Science and Engineering Conference (MSEC), , MSEC 2010-34342, Erie, PA, USA, October 12-15.