

**AN EXPERIMENTAL INVESTIGATION
ON PARTIAL-DUCTILE MODE GRINDING OF SILICON**

MOHAMED KONNEH

**A thesis submitted in fulfilment
of the requirements for the award of the degree
of Doctor of Philosophy**

**Faculty of Mechanical Engineering
Universiti Teknologi Malaysia**

NOVEMBER 2002

ACKNOWLEDGEMENTS

IN THE NAME OF ALLAH, THE GRACIOUS, THE MERCIFUL

I first of all express my sincere thanks to the Almighty Allah (God) for giving me the strength and courage to face all numerous challenges in my life.

My sincere and profound gratitude goes to Professor Dr. V. C. Venkatesh for not only his supervision which made this work a success but also his relentless financial and moral support during my studentship. I take this opportunity and extend my gratitude to Prof. Dr. K. S. Kannan whose financial support facilitated my first registration for this Ph.D. programme. I am particularly grateful to Prof., Muhammad Afifi Abdul Mukti for both his financial and moral support throughout my stay in UTM. Thanks are due to Intel Malaysia, Penang for its research grant on "Milling of Silicon Dies to get Mirror Finish", Vote 68837 that supported my study through Prof. Dr. V. C. Venkatesh.

I am very grateful to all the members of staff of the Faculty of Mechanical Engineering, especially Prof. Dr. Mohamed Awaluddin Shaharoun whose door has always been opened to me throughout my stay in UTM. Brother Izman bin Sudin deserves special thanks because without his relentless assistance in virtually everything during my pursuance of this degree, this research work would have been hardly completed. My appreciation is extended to Brother Noordin Mohamed Yusof for his invaluable suggestions that were helpful in my study. Special thanks go to Dr. Safian Sharif, the then Head of Production and Machine tool laboratories, for his assistance to me when there were technical problems. I am mindful of the help from my colleague Thet Thet Mon; my appreciation is extended to her. More thanks are due to all the technicians the Machine, Production and Materials Laboratories, especially Brother Sazali Ngadiman, for their cooperation and assistance during my experimental work. I am grateful to Professor Rahman and his staff in the Advanced Manufacturing Laboratory of the National University of Singapore for allowing me to use their measurement facilities.

Paramount Chief Bai S. Coomber and his wife Mrs. Dorothy K. Coomber deserve invaluable gratitude for the role they played in my educational life. I am deeply indebted to Dr. George J. Komba-Kono whose financial support paved my way to Malaysia for further studies. I am most grateful to my wife Isatu, whose relentless patience and encouragement during my study pushed me to the completion of the study programme. Sincere thanks are due to Brothers Fomba V. Sannoh, Adama Fofana and Mamodu Galy and their families for their moral support during my studentship. To my fellow international students in Universiti Teknologi Malaysia, particularly Brother Elhadi Badawi, I say to them than you, for their assistance at needy times throughout my study period in the university.

ABSTRAK

Tumpuan utama penyelidikan ini adalah untuk mencanai mod mulur secara persis (menggerek) ke atas permukaan rata silikon, terutamanya ke atas cip silikon tersepadu (I.C.), yang mana ketebalannya kira-kira 700 μm dan permukaan atasnya diselaputi dengan satu lapisan silikon nitrida. Penghasilan jumlah yang besar jalur separa mulur di atas permukaan silikon setelah pemesinan dapat mengurangkan masa penggilapan secara mendadak. Ini sangat penting terutama sekali dalam pembuatan cip dan industri optik bagi analisis kegagalan. Analisis kegagalan adalah satu teknik yang biasanya dilakukan untuk mencari sebarang kegagalan dalam produk siap I.C. Dalam industri pembuatan cip, analisis dilakukan ke atas I.C. dan silikon yang telah siap tanpa kecacatan dan permukaannya adalah seperti cermin. Pencanaian, pemelasan dan/atau operasi penggilapan diperlukan untuk mendapatkan permukaan yang licin. Pencanaian persis dalam keadaan mod mulur menjadi kritikal dan merupakan operasi pemesinan terpenting kerana kerosakan pada atas dan di bawah permukaan akan dikurangkan. Ini menghasilkan kualiti permukaan yang baik dari segi kemas permukaan dan kerataan dan pada masa yang sama dapat menjana jumlah jalur mulur yang maksimum ke atas permukaan yang dimesin. Disebabkan bilangan cip I.C. yang terhad, bahan silikon selain daripada silikon I.C. telah juga di uji bagi tujuan perbandingan. Silikon seperti bahan keras dan rapuh yang lain sangat dikenali mempunyai kebolehmeseinan yang rendah melainkan ia dimesin dalam keadaan mod mulur. Pemesinan mod mulur adalah proses yang membuatkan bahan rapuh berkelakuan seperti bahan mulur. Teknik pemesinan kos rendah telah dihasilkan untuk membantu pencanaian kawasan kecil secara mod mulur separa ke atas silikon nipis seperti wafer. Mesin penggerek menegak CNC MAHO telah diubahsuai secara khusus dengan dilengkapi alat tambahan peningkat kelajuan berkuasa rendah. Pusingan spindal bagi alat tambahan ini digerakkan dengan angin mampat untuk melakukan proses pencanaian intan. Lekapan khusus telah direkabentuk dan dipasang untuk memegang benda kerja serta mencegah mereka dari berlakunya keretakan semasa pemesinan. Kedua-dua teknik tradisional dan statistik telah digunakan dalam merekabentuk ujikaji dan seterusnya menganalisis keputusan dalam penyelidikan ini. Alat dinamometer *Kistler* (Compacdyn) yang mampu mengukur daya pemesinan yang rendah telah digunakan untuk mengukur daya semasa pemesinan. Form Talysurf, Surfcom, mikroskop berdaya atom telah digunakan untuk mengukur parameter tekstur permukaan. Teknik mikroskop optik dan imbasan elektron digunakan bersama dengan alat penganalisa permukaan Surfcom dan mikroskop berdaya atom untuk menganalisa morfologi permukaan silikon yang di mesin. Hasil kajian mendapati bahawa jumlah jalur mulur tidak sahaja bergantung kepada uluran dan kedalaman potongan tetapi ia juga bergantung kepada saiz grit intan dan kepadatannya. Teknik pemesinan pencanaian telah menghasilkan kemas permukaan canaian serendah 50nm dan daya pemesinan sekitar 0.8 Newton. Kerataan permukaan yang dimesin adalah sangat baik. Satu model kekasaran permukaan (R_a) bagi pencanaian persis silikon nipis telah dihasilkan.

ABSTRACT

This research work was primarily concentrated on precise ductile-mode grinding (milling) of flat surfaces of silicon, mainly Integrated Circuit (IC) silicon chips (dies), which were about 700 μm thick and the top of their surfaces covered with a silicon nitride layer. Substantial amount of partial-ductile streaks on a machined silicon surface shortens polishing time dramatically. This is of vital importance particularly in chip-making and optical industries for failure analysis. Failure analysis is a technique usually practised for locating a fault in a finished IC product. In chip-making industries, the analysis is done on the damage-free mirror-like finished silicon die of the IC. Grinding, lapping and/or polishing operations are required to get such a smooth surface. Precision grinding in a ductile mode therefore remains the critical and most important machining operation as the surface and sub-surface damages will be minimized. This results in good quality surface in terms of surface finish and flatness and at the same time generating the maximum amount of ductile streaks on the machined surface. Silicon material other than the IC silicon was also tried out for purpose of comparison and because of limited number of IC chips. Silicon like any hard and brittle material is well known for its low machinability unless it is machined under ductile mode condition. Ductile mode machining is a process that makes brittle materials to behave like ductile materials. A low cost machining technique, which facilitates partial-ductile mode grinding of small areas on thin wafer-like silicon, was developed. A specially modified conventional MAHO CNC Vertical Milling Centre that has an air driven low powered high-speed attachment (precision jig grinder) facilitated the diamond grinding. Special fixtures were designed and fabricated that held the workpieces in position and prevented them from damage during machining. Both traditional and statistical techniques for designing of experiments and subsequent analysis of results were employed in this study. A low cutting force dynamometer (Compacdyn) was used to measure cutting forces. Form Talysurf and Surfcom Surface Analysers and Atomic Force Microscope were used to measure surface texture parameters. Optical, Scanning Electron microscopy techniques, together with the Surfcom Surface Analyser and Atomic Force Microscope, were used to examine the surface morphology of the machined silicon surfaces. It was found that the amount of ductile streaks generated on a work-piece surface was not only dependent on feed and depth of cut but also on the grit size of diamond abrasive. The machining technique of grinding yielded ground surfaces with R_a as low as 50 nm, and forces around 0.8 Newton. Flatness of the machined surfaces is very good. A model of surface roughness (R_a) for precision grinding of thin silicon has been established.

II	PRECISE MATERIAL REMOVAL MECHANISMS IN BRITTLE MATERIALS DURING ABRASIVE MACHINING	25
2.1	Introduction	25
2.2	Grinding from conventional perspective	26
2.3	Abrasives	27
	2.3.1 Abrasives and coolants	28
2.4	Grinding wheels	29
	2.4.1 Grinding wheel specifications	30
	2.4.1.1 The grain structure	30
	2.4.1.2 The wheel grade	31
	2.4.1.3 The wheel structure	31
	2.4.1.4 Bond and types	32
	2.4.2 Marking systems of grinding wheels	33
	2.4.3 Wheel selection and grindability	34
2.5	Basic grinding mechanism of material removal	35
2.6	Types of grinding operations	37
	2.6.1 Cutting force components in turning, drilling, milling and grinding	39
2.7	Mechanics of grinding	41
	2.7.1 Grain depth of cut	41
	2.7.2 Energy expended during grinding	44
2.8	Temperature effect in grinding	45
2.9	Grinding wheel wear	46
	2.9.1 Mechanisms of grinding wheel wear	47
	2.9.1.1 Attritious wear	48
	2.9.1.2 Grain fracture	49
	2.9.1.3 Bond fracture	50
2.10	Dressing and truing of grinding wheels	50
2.11	Techniques for dressing grinding wheels	50
2.12	Precision grinding	52
2.13	Material removal mechanisms in brittle materials	53
	2.13.1 Johnson' model for elastic-plastic indentation of brittle materials	59
2.14	Microcrack-free of damage-free grinding	60

2.15	Ductile-mode machining of brittle materials	61
2.16	Principle of ductile-mode machining	63
	2.16.1 Ductile regime turning	65
	2.16.2 Ductile regime grinding	69
2.17	Summary	70
III	SURFACE TECHNOLOGY AND THE ASSESSMENT OF SURFACE TEXTURE AND INTEGRITY	74
3.1	Introduction	74
3.2	Surface Technology	75
	3.2.1 Characteristics of manufactured surfaces	75
	3.2.2 Surface texture	76
	3.2.2.1 Surface roughness and surface finish	78
	3.2.3 Surface Integrity	83
3.3	Assessment of surface texture	83
	3.3.1 Effect of magnification on surface profile recording	84
3.4	Instrumentation for measuring smooth surfaces	85
	3.4.1 Comparison of Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM)	86
3.5	Summary	88
IV	EXPERIMENTAL MATERIALS, EQUIPMENT AND DESIGN OF EXPERIMENTS	89
4.1	Introduction	89
4.2	Work materials	89
4.3	Tool materials	91
4.4	Experimental equipment and Instruments	92
4.5	Design of experiments	93
	4.5.1 The traditional approach to design of experiments	93
	4.5.2 The statistical approach to design of experiments	94
4.5	Summary	95

V	EXPERIMENTAL DETAILS	96
5.1	Introduction	96
5.2	Independent and dependent variables	96
5.3	Experimental set-up system	97
5.3.1	Machining set-up	98
5.3.2	Grinding pin dressing technique	99
5.4	Experimentation	99
5.4.1	Stage I: The preliminary investigations	100
5.4.1.1	Stage I-Part I: Machining of IC silicon chips using electroplated diamond grinding pins	100
5.4.1.2	Stage I-Part 2: Machining of IC silicon chips using resin-bonded diamond grinding pins	102
5.4.2	Stage II: The intermediary investigations	104
5.4.3	Stage III: The final experimental investigations	106
5.4.3.1	Stage III-Part 1: Machining of IC silicon chips using 64 μm resin-bonded diamond grinding pins with central holes	106
5.4.3.2	Stage III-Part 2: Machining of IC silicon chips using 91 μm resin-bonded diamond grinding pins with central holes	107
5.4.3.3	Stage III-Part 3: Machining of L-P silicon using 64 μm resin-bonded diamond grinding pins with central holes	108
5.4.3.4	Stage III-Part 4: Machining of IC silicon chips using 64 μm resin-bonded diamond grinding pins with central holes at 15 μm DOC and feed from 2.5 – 22.5 mm/min	109
5.4.3.5	Stage III-Part 5: Machining of IC silicon chips using 64 μm resin-bonded diamond grinding pins with central holes for development of a surface roughness model	110
5.5	Summary	111

VI	RESEARCH FINDINGS AND DISCUSSIONS	112
6.1	Introduction	112
6.2	Stage I-Findings from the Preliminary investigations	114
6.2.1	Stage I-Part 1: Discussion of the surface roughness and ductile streaks obtained from the machining of IC silicon chips using electroplated diamond grinding pins	114
6.2.2	Stage I-Part 2: Discussion of the surface roughness and ductile streaks obtained from the machining of IC silicon chips using resin-bonded diamond grinding pins	117
6.3	Stage II: Findings from the intermediary investigations	123
6.3.1:	Discussion of the surface roughness and ductile streaks obtained from the machining of IC silicon chips using resin-bonded diamond grinding pins with central holes	123
6.4	Stage III-Findings from final investigations	135
6.4.1:	Stage III-Part 1: Discussion of the surface roughness and ductile streaks obtained from the machining of IC silicon chips using 64 μm resin-bonded diamond grinding pins with central holes	135
6.4.2:	Stage III-Part 2: Discussion of the surface roughness and ductile streaks obtained from the machining of IC silicon chips using 91 μm resin-bonded diamond grinding pins with central holes	137
6.4.3:	Stage III-Part 3: Discussion of the surface roughness and ductile streaks obtained from the machining of L-P silicon using 64 μm resin-bonded diamond grinding pins with central holes	137
6.4.4:	Discussion of the cutting forces from the machining of IC silicon chips and L-P silicon using 64 μm grinding pins with central holes, and the machining of IC silicon chips using 91 μm with central holes	139

6.4.4.1	The cutting forces in the tangential direction	141
6.4.4.2	The cutting forces in the normal direction	141
6.4.4.3	The specific grinding energy	143
6.4.4.4	The coefficient of friction	146
6.4.5:	Stage III-Part 4: Discussion of the ductile streaks generated on IC silicon chips and L-P silicon when they were machined using 64 μm and 91 μm resin-bonded diamond grinding pins with central holes	148
6.4.6:	Stage III-Part 5: Discussion of the development of a model for surface roughness (R_a) results from the machining of IC silicon chips using 64 μm resin-bonded diamond grinding pins with central holes	156
6.5	Discussion of the wear of the experimental resin-bonded diamond grinding pins	160
6.6	Summary	161
VII	CONCLUSIONS AND RECOMMENDATIONS	162
7.1	Introduction	162
7.2	Conclusions	162
7.2.1	Contributions form the research work	165
7.3	Recommendations for future work	166
VII	REFERENCES	167
VIII	APPENDICES	
Appendix A	Publications	179
Appendix B	Specifications of grinding wheel and pins	181
Appendix C	Experimental equipment and instruments	185
Appendix D	Graphs of grinding forces	191

LIST OF TABLES

TABLE NO.	TITLE	PAGE
1.1	Precision products classed into mechanical, Electrical and Optical parts	18
2.1	Change in model parameters with change in tool rake angle during diamond turning of germanium	68
3.1	Sampling lengths for roughness measurement	81
3.2	Evaluation lengths and meter cut-off	82
3.3	Sampling lengths for the measurement of R_a of non-periodic profiles	82
3.4	Resolution and range of some instruments used to examine smooth surfaces	86
3.5	The characteristics of SEM and AFM	87
5.1	Cutting conditions when machining IC silicon chips using electroplated grinding pins at the preliminary Stage I of the experiments	100
5.2	Cutting conditions when machining IC silicon chips using -bonded diamond grinding pins at the preliminary Stage I, Part 2 of the experiments	102
5.3	Cutting conditions when machining IC silicon chips using 64 μm 91 μm and 126 μm resin resin-bonded diamond grinding pins at the intermediary Stage II of the experiments	105
5.4	Cutting conditions when machining IC silicon chips using 64 μm resin-bonded diamond grinding pins at the final Stage III Part 1 of the experiments	107

5.5	Cutting conditions when machining IC silicon chips using 91 μm resin-bonded diamond grinding pins with central holes at Stage III, Part 2	107
5.6	Cutting conditions when machining L-P silicon using 64 μm resin-bonded diamond grinding pins at the final Stage III, Part 3 of the experiments	108
5.7	Cutting conditions when machining IC silicon chips using 64 μm resin-bonded diamond grinding pins at the final Stage III Part 4 of the experiments to determine the critical and optical conditions for generation of partial-ductile streaks	109
5.8	Cutting conditions when machining IC silicon chips using 64 μm resin-bonded diamond grinding pins at the final Stage III Part 5 of the experiments for the development of a surface roughness model by RSM	110
6.1	Average roughness results when IC silicon dies were machined with electroplated grinding pins	114
6.2	Stage II- Average roughness results for machining IC silicon dies using 64 μm resin-bonded grinding pins	123
6.3	Stage II- Average roughness results for machining IC silicon dies using 91 μm resin-bonded grinding pins	126
6.4	Stage II- Average roughness results for machining IC silicon dies using 126 μm resin-bonded grinding pins	127
6.5	Stage III- Average surface roughness versus depth for IC silicon die surfaces ground using 64 μm grinding pins for feed from 2.5 to 47.5 mm/min and DOC from 3 to 27 μm	136
6.5	Comparison of grinding of IC silicon with L-P silicon (from Group II-VI optical industry)	138
6.7	Cutting forces from the machining IC silicon chips using 64 μm resin-bonded diamond grinding pins at feed from 2.5 mm/min and DOC from 3 to 27 μm .	140
6.8	Cutting force results for L-P silicon surfaces ground using 64 μm grinding pins for feed = 2.5 and DOC from 3 to 27 μm	140

6.9	Cutting force results for IC silicon die surfaces ground using 91 μm grinding pins for feed = 2.5 and DOC from 3 to 27 μm	140
6.10	Comparison of grinding coefficients	146
6.11	Cutting force results from the machining of IC silicon die using 64 μm grinding pins for feed from 2.5 to 22.5 mm/min and DOC =15 μm	151
6.12	Analysis of surface roughness results by RSM	157
6.13	ANOVA for surface roughness obtained from the machining of IC silicon chips using 64 μm resin-bonded diamond grinding pins	157

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Moore's Law predicting the IC integration to double every 18 months	2
1.2	Accelerometer for Airbags (Analog Devices)	5
1.3	Physical and mechanical properties of silicon and carbon steel	6
1.4	Flowchart for processing silicon based devices	7
1.5	The Czochralski process for growing single-crystal ingot of silicon	7
1.6	Basic sequence of the processing steps in the production of IC chips	8
1.7	Cylindrical grinding operation used in shaping silicon ingot	8
1.8	Surface grinding of silicon wafer after wire-sawing operation	9
1.9	The scale of things where micro-technology and nano-technology fit	15
1.10	Reduction in pattern dimensions of integrated circuits	16
1.11	Modified Taniguchi's chart showing achieved machining accuracy at decade intervals	17
2.1	Schematic illustration of a physical model of a grinding wheel showing its structure, wear and fracture patterns	29
2.2	Standard method of wheel marking	34
2.3	Three modes of grain actions in grinding	36
2.4	Various stages of grinding with regard to depth of cut	36
2.5	Types of grinding operations	38
2.6	Force components in machining operations	40
2.7	Force components on experimental grinding wheel	41

CONTENTS

CHAPTER	TOPIC	PAGE
	TITLE	i
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRAK	v
	ABSTRACT	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xiii
	LIST OF FIGURES	xvi
	ABBREVIATIONS AND DEFINITIONS OF TERMS	xxii
I	INTRODUCTION	1
	1.1 Overview	1
	1.2 Precision Engineering	13
	1.2.1 The scale of things in daily life	14
	1.2.2 Four classes of achievable machining accuracy	14
	1.3 Progress in precision finishing	19
	1.4 Background of the research	20
	1.5 Problem statement	21
	1.6 Objectives of the research	22
	1.7 Significance of the project	22
	1.8 Scope of the research	23
	1.9 Outline of the thesis	23
	2.0 Summary	24

2.8	Simple multi-toothed milling operation, which is similar to grinding	42
2.9	Schematic illustration of the surface grinding process	43
2.10	Principal grinding wheel wear mechanisms	48
2.11	Taniguchi's established relationship between fine cutting and shear stress	52
2.12	Molecular dynamic simulation of cutting with large negative rake angle tool	54
2.13	Progression of cutting force actions from positive rake tool cutting to indentation sliding	55
2.14	Localized deformation and fracture due to indentation	57
2.15	Chips from alumina ceramics and hardened steel	58
2.16	Model for elastic-plastic indentation of brittle materials	59
2.17	Characterisation of machined surfaces of brittle materials	62
2.18	Konig's model for ductile mode machining	63
2.19	Miyashita's chart for conventional and nano-grinding processes	64
2.20	Model for chip removal with small and large depths of cut	64
2.21	Blackley and Scattergood's model for single-point diamond turning	66
2.22	Graph showing single-point diamond turning with different rake angles	68
3.1	A magnified cross-section of a typical metal part surface	75
3.2	Features of surface texture of a machined, self-finished and other surfaces	76
3.3	Possible lays of a surface texture	77
3.4	Symbols with identification labels used to define surface texture	78
3.5	A machined surface profile indicating traversed, evaluation and sampling lengths	79
3.6	Commonly used parameters that define the roughness of a surface	79
3.7	A surface texture representing the combined effects of several causes	81
3.8	Surface texture having the same maximum height but different geometric profiles	84

3.9	Effect of different horizontal magnifications on a surface profiles	85
3.10	Measurement range and resolution of SEM and AFM	88
4.1	Integrated Circuit chips before and after machining	90
4.2	A precision cut block of L-P silicon (from Group II-VI optical industry) glued onto a locally fabricated aluminium fixture	90
4.3	Tool materials used for experimentation	91
5.1	The experimental set-up system	97
5.2	Machining set-up for grinding silicon	98
5.3	Dressing technique using aluminium oxide stick used for dressing resin-bonded diamond grinding pins before every experimental trial run	99
5.4	A locally fabricated Fixture A for holding IC silicon chips in position at the preliminary Stage I, Part 1 of the experiment when using electroplated diamond grinding pins	101
5.5	A locally fabricated Fixture B for holding IC silicon chips in position at the preliminary Stage I, Part 2 of the experiment when using resin-bonded diamond grinding pins	103
5.6	A locally fabricated Fixture C for holding IC silicon chips in position at the intermediary Stage II and final Stage III of the experiment when using resin-bonded diamond grinding pins	105
5.7	A locally fabricated Fixture D for holding L-P silicon in position at the final Stage III of the experiment when using resin-bonded diamond grinding pins	108
6.1.	Flowchart for evaluation of experimental results	113
6.2	Optical micrograph of an IC silicon die ground with a 3-mm diameter electroplated diamond-grinding pins (Stage I, Part1)	115
6.3	SEM image of an IC silicon die ground with a 5-mm diameter electroplated diamond grinding pins (Stage I, Part 1)	115
6.4	Optical micrograph of an IC silicon die ground with a 3-mm diameter electroplated diamond-grinding pins showing surface damages (Stage I, Part 1)	116

6.5	SEM image of ground IC silicon die surface using a 5-mm diameter resin diamond grinding pin showing ductile streaks (Stage I, Part 2)	118
6.6	AFM image of ground IC silicon die surface using a 5-mm diameter resin diamond grinding pin showing ductile streaks (Stage I, Part 2)	119
6.7	SEM image of ground IC silicon die surface showing distinct region of fractures along the central track of the surface (Stage I, Part 2)	120
6.8	Form Talysurf profiles of a ground IC silicon die using grinding pins with and without central holes (Stage I, Part 2)	121
6.9	Form Talysurf profiles of a ground IC silicon die using grinding pin with central hole showing R_a and waviness profiles (Stage I, Part 2)	122
6.10	A profile illustrating relationship between W_a (waviness height) and S_m (waviness spacing) at Stage II	124
6.11	Surface roughness versus depth of cut for machining IC silicon dies with 64 μm diamond grinding pins for feed from 5 to 35 mm/min and DOC from 5 to 25 μm (Stage II)	125
6.12	Grinding pin surfaces examined before and after machining	125
6.13	Surface roughness versus depth of cut for machining IC silicon dies with 91 μm diamond grinding pins for feed from 5 to 35 mm/min and DOC from 5 to 25 μm (stage II)	126
6.14	Surface roughness versus depth of cut for machining IC silicon dies with 126 μm diamond grinding pins for feed from 5 to 35 mm/min and DOC from 5 to 25 μm (Stage II)	127
6.15	SEM images of IC silicon die surfaces ground using 64 μm grinding pins for feed from 5 to 35 mm/min and DOC from 5 to 25 μm (Stage II)	129
6.16	SEM images of IC silicon die surfaces ground using 91 μm grinding pins for feed from 5 to 35 mm/min and DOC from 5 to 25 μm (Stage II)	130

6.17	SEM images of IC silicon die surfaces ground using 126 μm grinding pins for feed from 5 to 35 mm/min and DOC from 5 to 25 μm (Stage II)	131
6.18	3-D Zygo image of IC silicon die surface ground using 64 μm grinding pins at 5 mm/min and depth of cut 5 μm (Stage II)	132
6.19	3-D Zygo image of IC silicon die surface ground using 64 μm grinding pins at 5 mm/min and depth of cut 15 μm (Stage II)	133
6.20	A 3-D Zygo image of IC silicon die surface ground using 64 μm grinding pins at 5 mm/min and depth of cu 25 μm (Stage II)	134
6.21	Average surface roughness versus depth of cut for the machining of IC silicon die surfaces ground using 64 μm grinding pins for feed from 2.5 to 47.5 mm/min and DOC from 3 to 27 μm (Stage III)	136
6.22	Plot of force results from the machining IC silicon dies with 64 μm grinding pins for feed from 2.5 to 47.5 mm/min and DOC from 3 to 27 μm (Stage III)	142
6.23	Grinding pin bottom surface showing grain fractures	143
6.24	Chip extrusion model showing how a workpiece undergoes plastic deformation	144
6.25	Grinding wheel bottom surfaces showing diamond grains/cm ²	145
6.26	SEM images of IC silicon die surfaces ground using 64 μm grinding pins for feed from 2.5 to 47.5 mm/min and DOC from 3 to 27 μm	152
6.27	SEM images of L-P silicon surfaces ground using 64 μm and images of IC silicon chips using 91 μm grinding pins for feed = 2.5 mm/min and DOC from 3 to 27 μm	153
6.28	SEM images of IC silicon die surfaces ground using 64 μm grinding pins for feed from 2.5 to 22.5 mm/min and DOC = 15 μm	154

6.29	Plot of specific energy versus for machining IC silicon with 64 μm grinding pin, feed from 2.5 to 22.5 mm/min and DOC = 15 μm	155
6.30	Contour plot of roughness results using RSM	159
6.31	3-D plot of roughness results using RSM	159
6.32	Resin bonded grinding pin illustrating curvature-like wear at its cutting edge	160

ABBREVIATIONS AND DEFINITION OF TERMS

SEM	- Scanning Electron Microscope
AFM	- Atomic Force Microscope
DOC	- Depth of cut
nm	- nanometer
μm	- micrometer
R_a	- The arithmetical average value of all absolute deviations of the roughness profile R from the centre line within the evaluation length generally 5 times the sampling length.
R_{max}	- The maximum individual peak to valley dimension of any sampling length occurring with the evaluation length.
R_t	- The maximum peak to valley height within the evaluation length or traversed length.
IC	- Integrated Circuit
Ge	- Germanium
Si	= Silicon
H-P silicon	- IC silicon
L-P silicon	- Silicon (from Group II-VI optical industry)
Ge	- Germanium
f	- feed rate
d	- depth of cut
l	- litre
N	- Newton
Ch1, 2, 3	- Channels 1, 2, 3
RSM	- Response Surface Methodology
ANOVA	- analysis of variance
F_x	- feed force component
F_z	- tangential force component

F_y	- thrust force component
FA	- Failure analysis
W_a	- Waviness height
S_m	- Waviness spacing

REFERENCES

- Andrae P., October (2000). "High-Efficiency Machining" Fabtech International, SME Manufacturing Engineering Magazine. Vol.125, No.4, 82-96.
- Balson, P. and Puna, R, (1991). "Diamond Wheel Selection Criteria for Grinding Advanced Engineering Ceramics". SME Technical Paper: EM91-196, 1-20.
- Besse, J. R., (1992). "Creep feed Grinding Concepts and Applications", SME Technical Paper: MMR 92-03.
- Bhushan, B. (1999). "Principles and Applications of Tribology". John Wiley & Sons, Inc. USA
- Bifano, T.G., Blake, P., Dow, T.A. and Scattergood, R.O., (1988). "Precision Machining of Ceramic Materials". American Ceramic Society Bulletin: 67(2), 1038-1044.
- Bifano, T.G., Dow, T.G., and Scattergood, R.O., (1991). "Ductile Regime Grinding: A new Technology for Machining Brittle Materials". Journal of Engineering for Industry: Vol. 113, 184-189.
- Blake, P. N. and Scattergood, R. O. (1990). "Ductile Regime Machining of Germanium and Silicon": J Amer Ceram Soc 73 (4).
- Blackley, S. and Scattergood, R.O. (1990). "Mechanics of Material Removal In Diamond Turning". Proceedings of ASPE Annual Meeting: Rochester, NY, USA, 68-71.

- Blackley, S. and Scattergood, R. O. (1991). "Ductile Regime Machining Model for Diamond Turning of Brittle Materials". *Journal of Precision Engineering*: Vol.13/2, 95-102.
- Brecker, J. N., (1972). "High Speed Grinding and Productivity". SME Publication: Edited by Bhateja, C. and Lindsay, R. 243-255.
- Bridgman, P. W., (1953). "Effects of Very High Pressures on Glass". *J of App. Phy.* 24: 405-413.
- Bridgman, P.W. (1953). "Studies in Large Plastic Flow and Fracture with Special Analysis on the Effect of Hydrostatic Pressure". McGraw Hill Co. New York.
- Brinksmeiser E., Tonshoff, H.K., Inasaki, I and Peddinghans, J. (1993). "Basic Parameters in Grinding". *Technical Reports, Ann. of CIRP, Vol.42 (2):* 795-799.
- Broese, G. A. and Veldkamp, J. D. B., (1982). "Machining of Hard and Brittle Materials", edited by Roy Williams. SME Publication, Dearborn, USA.
- British Standard Institution. "Assessment of Surface Texture: Methods and Instrumentation". BS 1134: Part 1 1988.
- British Standard Institution. "Assessment of Surface Texture: Guidance and General Information." BS 1134: Part 2 1990.
- Chee, W.K (1996). "Surface Integrity Studies on Hard and Soft Infra-red Plano and Spherical Lenses". Nanyang Technological university, Singapore: BEng Dissertation.
- Cornell, J. A., (1990). "How to Apply Response Surface Methodology": 2nd ed. American Society for Quality Control.

- Corsini, A.M., and Indge, J.H. (1990). "Precise Abrasive Machining of Flat Surfaces in Production": SME Technical Paper, MR90-399.
- Fang, F.Z., and Venkatesh, V.C., (1998). "Diamond Turning of Silicon with Nanometric Finish". Annal of the CIRP 47/1: 45-49.
- Gerk, A. P. and Tabor, D. (1978). "Indentation Hardness and Semiconductor-metal Transition of Germanium and Silicon". Nature, 271: 732-733.
- Gorczyca , F. E., (1987). "Application of Metal Cutting Theory". Industrial Press, Inc.
- Groover, M. P. (1996)." Fundamentals of Modern Manufacturing: Materials, Processes and Systems". Prentice-Hill International, Inc, USA.
- Heuta, M. and Malkin, S. (1976). "Grinding of Glass, Mechanics of the process": Journal of Engineering for Industry, 459-467.
- Hwang, T.W., Evans, C. J. and Malkin, S. (2000). "An Investigation of High Speed Grinding with Electroplated Diamond Wheels". Annals of the CIRP: Vol. 49/1/2000, 245-246
- Ikawa, N., Donaldson, R.R., Komanduri, R., Konig, W., McKeown, P.A., Moriwaki, T., and Stowers, I. F. (1991). "Ultra Precision Metal Cutting, The Past, Present, and Future". Annals of the CIRP: Vol.40, No.2: 587-594.
- Inasaki, I. (1987). "Grinding of Hard and Brittle Materials". Annals of the CIRP: Vol.36, No. 2: 463-471
- Inasaki, I. (1986). "High-Efficiency Grinding of Advanced Ceramics". Annals of the CIRP: Vol.35, No.1: 211-214.
- Jackson, M.J., (2002). "Wear of Perfectly Sharp Abrasive Grinding Wheels". SME Technical Paper: MR02-157.

- John, O.W. (1966). "Damage produced in Germanium at Room Temperature by Indentation". J. Appl Phys: Vol.37, No.7, 2521-2526.
- Johnson, K.L., (1970). "The Correlation of Indentation Experiments". J.Mach. .Phy. Solids: 18: 115-125.
- Johnson, W and Moller, P.B (1973). "Engineering Plasticity": D. Van Nostrand, Co. London, U.K.
- Jonathan, C. et al. (1995). "Origin of the Ductile Regime in Single-Point Diamond Turning of Semiconductors". Journal of American Ceramic Society: (8) 2015-20.
- Kaczmarek, J., (1976). "Principles of Machining by Cutting Abrasion and Erosion": Peter Peregrinus: Stevenage Herts U.K.
- Kalpakjian, S. (1995). "Manufacturing engineering and Technology". Addison-Wesley Publishing Company, Inc., USA.
- Kloche, F., Brinksmeier, E., Evans, C., Howes, T., Inasaki, I., Minke, E., Tonshoff, H. K., Webster, J. A. and Stuff, D. (1997). "High speed grinding- Fundamental and State of the Art in Europe, Japan and USA". Annals of the CIRP: Vol. 46/2/: 715-724
- Komanduri, R., Lucca, D.A., and Yani, Y., (1997). "Technological Advances in Fine Abrasive Processes". Annals of the CIRP: Vol.46, No.2: 545-596.
- Konig, W., Tonshooff, H.K., Fromlowtz, J., and Dennis, P. (1986). "Belt Grinding". Annals of the CIRP: Vol.35, No.2: 487-494
- Lambert, B. K. and Taraman, K., (1972). "Response Surface Models for Metal Removal Analysis". SME Technical Paper: MR72-137, 1-13.

- Lawn, B. R., and Evans, A. G. (1977). "A Model for Crack Initiation in Elastic/Plastic Indentation Fields: J of Mat Sci 12: 2195-2199.
- Lawn, B. R., Evans, A. G., and Marshall, D. B. (1980). "Elastic/Plastic Indentation Damage in Ceramics". The Median/Radial Crack System: J Am. Cer. Soc., 63: 574-581.
- Lawn, B., and Wilshaw, R., (1975). "Review: Indentation Fracture, Principles and Applications". Journal of Material Science: 10, 1049-1081.
- Li Bo Li Bo Zou, Jiyuo, Li Hui, Chong, Yew Hug, Fang Wei and Gong Haiqing, (2000). "Cutting Force Measurement in High Speed Milling of Plastic Prototype": ICoPE. Singapore Expo. 494-499.
- Lindberg, R. A., (1990). "Processes and Materials of Manufacture". Allyn and Bacon Publisher.
- Lonardo, P.M., Trumpold, H. and De Chiffre, L., (1996). "Progress in 3D Microtopography Characterization". Annals of the CIRP, 45/2: 589-598.
- Lucca, D.A., Rhoner, R.L., and Komanduri, R., (1991). "Energy Dissipation in Ultraprecision Machining of Copper". Annals of CIRP, 40/1:69-72.
- Malkin, S. (1975). "Specific Energy and Mechanisms in Abrasive Processes": Proceedings of NAMRC III, 453-463.
- Malkin, S. (1989). "Grinding Technology". Ellis Harwood Ltd, Chichester West Sussex, U.K.
- Malkin, S., and Hwang, T.W., (1996). "Grinding Mechanisms for Ceramics". Annals of CIRP: Vol.45, No.2: 569-580.
- Malkin, S. and Joseph, N. (1975). "Minimum Energy in Abrasive Processes". Wear: 32, 1975, 15-23.

- Malkin, S. (1981). "Grinding Mechanisms for Metallic and Nonmetallic Materials".
Proceedings of NAMRC II, .253-239
- Marshal, E.R., and Shaw M.C. (1952). "Forces in Dry Surface Grinding". Trans.
ASME, Vol. 74:51-59.
- Marshall, D. M., Lawn, B. R., and Evans, A. G., (1982). "Elastic/Plastic Indentation
Damage in Ceramics". The Lateral Crack System J of Am Cer. Soc. 65:
561-566.
- Mayer, Jr. J.E., and Price, A.M. (2001). "Specific Grinding Energy Causing Thermal
Damage in Helicopter Gear Steels'. SME Technical Paper: MR01-346.
- McGeough, J. A. (1988). "Advanced Methods of Machining".Chapman and Hall
Ltd.London.
- McKeown, P. (1996). "From Micro-to Nano-Machining towards the Nanometer
Era". Sensor Review, 16(2): .4-10.
- McKeown, P. A, (1987) "The Role of Precision Engineering in Manufacturing of the
Future". Annals of CIRP:Vol.36, No.2: 495-502.
- McKeown, P.A., (1995). "High Precision Manufacturing in Advanced Industry
Economy". Lecture at GINTIC, National University of Singapore.
- Miyashitta, M. (1989). "Brittle/Ductile Machining". Fifth International Seminar on
Research Engineering: Monterey, CA, USA.
- Molley, P., Schinder, M.G. and Doll, W. (1987). "Brittle fracture mechanisms in
Single Point Glass Abrasion". International Technical Symposium on Optical
and Electro-optical Applied Science and Engineering, The Hague, NL,
(SPIE Vol 802.

- Nakasuji, T., Kodera, S. Hara, S. Matsunaga, H. Ikawa, N., and Shimada, S. (1990). "Diamond Turning of Brittle Materials for Optical Components". *Annals of CIRP: Vol.39, No.1: 89-92.*
- Ngoi, B.K.A., and Sreejith, P.S. (2000). "Ductile Regime Finishing-A Review". *Int. J. Adv. Manuf. Technol. 16: 547-550.*
- Ong, N.S. and Venkatesh, V.C. (1988). "Semi-ductile grinding and polishing of Pyrex". *Journal of Material Processing Technology: (83), 261-266.*
- Pandit, S.M. and Sathyanarayanan, G. (1982). "A Model for Surface Grinding based on Abrasive Geometry and Elasticity". *ASME Journal of Engineering for Industry: Vol.104, No.4: 349-357]*
- Pandit, S.M., and Sathyanarayanan, G., (1984). "Surface Roughness and Specific Energy with Progress of Cut in Grinding" *SME Technical Paper: MR84-531.*
- Pei, Z.J. and Fisher, G.R. (2001). *Surface Grinding in Silicon Wafer Manufacturing.* *SME technical Paper: MR01-271, 1-8*
- Puttick K. E., Whitmore, L. C., Chao, C. L., and Gee, A. E., (1994). "Transmission Electron Microscopy of Nanomachined Silicon Crystals". *Phil., Mag A, Vol.69. 91-103.*
- Puttick, K. E., Shahid, M. A. Hosseini, M. M., (1979). 'Size Effects in Abrasion of Brittle Materials". *J Phys D App Phys.: 12:195-202.*
- Ramesh, R., Ramesh, K., Yeo, S. H., Gowri, S. and Zhou, L., (2001). "Experimental Evaluation of Super High-Speed Grinding of Ceramics". *Inter. J. Adv. Manuf. Technol 17: 87-92.*
- Reichenbach, G. S., Mayer, I. E., Kalpakcioglu, S., Shaw, M. C. (1995). "The Role of Chip Thickness in Grinding". *Trans. ASME. Vol. 18. 847-850.*

- Robert, Holz, (1988). "Grinding with Diamond and CBN". WINTER Diamond and CBN 1st edition: Ernest Winter and Sons, Germany.
- Rudiger, R., and Inasaki, I., (1995). "Investigation of Surface Integrity by Molecular Dynamic Simulation": Annals of the CIRP: Vol.44, No.1. 295-298.
- Salje, E., and Paulmann, R. (1988). 'Relations between Abrasive Processes". Annals of CIRP: Vol. 37, No.2. 641-648.
- Shaji, S. and Radhakrishnan, V. (2002). "Investigation on Surface Grinding with Barium Fluoride as Lubricant": 2nd World Engineering Congress, 22-25 July Sarawak, Malaysia, 209-213
- Shaw M.C. (1996). "Principles of Abrasive Processing": Oxford University Press Inc., New York, USA.
- Shaw, M.C. (1957). "Metal Cutting Principles": Oxford University Press, USA.
- Shaw, M.C. (1995). "Precision Finishing". Annals of the CIRP: Vol.44, No.1. 343-348.
- Shaw, M.C. (1995). "Energy Conversion in Cutting and Grinding" Annal of the CIRP: Vol. 45, No.1. 101-104.
- Shaw M. C., "The Size Effect in Metal Cutting - to be published in SADHANA, Academy Proceedings in Engineering Sciences, Indian Academy of Sciences, Bangalore 560080, India.
- Shimida, S., Ikawa, N., Inamura, T., Takezawa, N., Ohmori, H. and Sata, T. (1995). "Brittle Transition phenomena in micro indentation and micro machining". Annals of CIRP: Vol.44, No.1. 523-526.
- Stephenson, D.A. and Agapiou, J.S. (1997). "Metal Cutting Theory and Practice": Marcel Dekker Inc. USA.

- Stewart, M. A., (2001). 'Specifying surface roughness': SME Technical Paper MR01-213.
- Strausser, Y. E. and Heaton. M. G., (1994). "Scanning Probe Microscopy Technology, Innovations". Santa Barbara, USA: American Laboratory, 1-2.
- Stout, K. J., (1994). "Three-dimensional surface topography: Measurement, Interpretation, and Application": Penton Press, United Kingdom.
- Syn, C. K, Taylor, J. S., Donaldson, R. R., Shimada, S. (1988). "Ductile Brittle Transition of Cutting Behaviour in Diamond Turning of Single Crystal Silicon": Proc. Jap. Soc. Prec. Eng, Kawaski, Japan.
- Syn, C.K., and Taylor, J.S., Ductile (1989). "Brittle Transition of Cutting Mode in Diamond Turning of Single Crystal Silicon and Glass". Poster Session: ASPE/IPES Conference, Monterey.
- Tabor, D., (1970). "The Hardness of Solids". Proc. of the Institute of Physics in Technology: Vol. 1: 145-179.
- Taniguchi N (1983). "Current Status in and Future Trends of Ultraprecision Machining and Ultrafine Materials Processing": Annals of CRIP: Vol.32, No.2. 573-582.
- Taniguchi N (1993). "The State of the Art of Nanotechnology for Processing of Ultraprecision and Ultrafine Products" ASPE Distinguished Lecture, Precision Engineering: 16:5-24.
- Tonshoff, H. K., V., Schmiedon, W., Inasaki, I., Konig, W., and Spur, G. (1990). "Abrasive Machining of Silicon". Annals of the CIRP: Vol.39, No.2: 621-635.
- Tummala, R. R. (2001). "Fundamentals of Microsystems Packaging". McGraw-Hill Company, Inc. USA.

- Venkatesh, V. C., Izman, S. and Konneh, M. (2000). "Ultra-Precision and High Precision Turning and Grinding of Brittle Materials". Asian Academy Seminar on Advanced Manufacturing Systems: Japan-India Cooperative Science Programme, Hyderabad, India, Dec. 3-12, 99-100.
- Venkatesh, V. C., Ahmad, Z. A., and Konneh, M. (2000). "Performance Studies of Alumina TiC-based Ceramic Tool Inserts when Turning Tool Steels". Proceedings of The 2nd International Conference on Advanced Manufacturing Technology, Johor, Malaysia, 91-105.
- Venkatesh V. C., Norizah, R., Konneh, M., Ourdjini, A., Teo, C., Ung, E.G. (2000). "Micromachining of Electronic Materials". Manufacturing Technology- Proceedings of 19th All India Manufacturing Technology, Design and Research Conference: Chennai, India. 723-728.
- Venkatesh, V.C., and Tan, C.P. (1990). "The Generation of Aspheric Surfaces on Thermal Imaging Materials". Proceedings of the ASPE Annual Meeting: Rochester, NY, 23-26.
- Venkatesh, V.C., Inasaki, I., Tonshoff, H.K., Nakagawa, T., and Marinescu, I.D. (1995). "Observations on Polishing and Ultra Precision Machining of Semiconductor Substrate Materials". Annals of the CRIP: Vol.44, No.2: 611-618.
- Venkatesh, V. C. (1999). "Machinability Database and Performance Evaluation of Advanced Cutting Tools". IRPA Vote 72196 (RM 289,750), 1999-2001
- Venkatesh, V.C. (1999). "Milling of Silicon Die to get Mirror Finish". Intel Vote 68837, (RM 132,000), 1999-2001
- Venkatesh, V.C. (1999) "Performance Evaluation of New Diamond Tools". IRPA, Vote 72255 (RM 266,950), 1999-2001

- Venkatesh, V.C. and Zhong, Z. (1995). "Manufacture of Spherical and Aspherical Surfaces on Plastics, Glass and Ceramics". Trans. NAMRI XXIII, Houghton, MI, May: 169-174
- Venkatesh, V. C., S. Izman, S, Sharif, T. T. Mon, M.Konneh, (2002). "Precision Grinding of Hard and Brittle Materials". The 2nd World Engineering Congress, Sarawak, Malaysia, 276-281.
- Senates, V. C., S. Inman, S, Shari, T. T. Mon, McKinney, (2003). "Ductile Streaks in Precision Grinding of Hard and Brittle Materials"- to be published in SADHANA, Academy Proceedings in Engineering Sciences, Indian Academy of Sciences, Bangalore 560080, India.
- Vorburger, T.Y., (1987). "Measurements of Roughness of very Smooth Surfaces" Annals of the CIRP: 36/2:503-509.
- Wang, X., Hong G. D., Zhang, J., Lim, B. L. Gong, H.Q. (2000). "Precision Patterning of Diamond Films for MEMS Application, International Conference of Precision Engineering, Singapore, 562-567.
- Whitehouse, D.J., (1994). "Handbook of Surface Metrology". Inst of Physics: Bristol, UK
- Whitehouse, D. J., Bowen, D. K., Venkatesh, V. C., Lonardo, P. and Bowen C. A., (1994). Gloss and Surface Topography. Annals of the CIRP. Vol.43, No.2: 541-549.
- Yeo E. H., Lim S. L., Wong Y. C. Lock C. H. and Mahmud A. (1988). "An Overview of Failure Analysis Techniques for Pentium and Pentium Pro Microprocessors". Intel Technology Journal, Q2, 1-11
- Yoshioka, J., Miyashita, M., Hashimoto, F. and Daitoh, M. (1984). "High precision Centre less grinding of glasses as a preceding operation in polishing": SME Technical Paper, MR84-542.

Zhong, Z., and Venkatesh, V.C. (1995). "Semi-Ductile Grinding and Polishing of Ophthalmic Aspherics and Spherics". *Annal of the CIRP*: Vol.44, No.1 339-342.