PERFORMANCE EVALUATION OF GRINDING AND LAPPING OPERATIONS FOR GENERATING ASPHERIC SURFACES ON GLASS MOULDS USING VERTICAL MACHINING CENTRE

PARAG SHASHIKANT VICHARE

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To my beloved mother and father

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ABSTRACT

The main purpose of the study is to investigate potentials of vertical machining centre to produce aspheric glass moulds. The use of vertical CNC machining centre is promoted in the study to make the process more flexible compared to dedicated aspheric generators used in optical industry. Glass moulds were rough ground and lapped using four diamond grinding cup wheels. Metal and resin bonded wheels were used in rough grinding and lapping operation with grit size of 151μm and 15μm respectively. Theoretical and experimental investigations of the grinding parameters and material behaviour that influence partial ductile mode have been discussed. Analysis encompasses the kinematics of the grinding process, characterization of grinding wheel topography, mechanism of material removal and conformity analysis between grinding wheel and glass mould. The grit depth of cut analysis explains the influence of the geometry of the conformity between wheel and glass mould, and which leads to some parametric relations in the grinding process. Image analysis technique was effectively used to observe the grinding wheel topography and ground surface. The experimental process results were compared with the available industrial samples and zone generation method for determining process performance. It was found that resin bonded wheel gave better surface finish and form accuracy as compared to metal bonded wheel and rest of other two samples in the rough grinding operation. Partial ductile machined area was observed in the lapping operation. Lapping results of the industrial samples were quite promising and closer to experimental samples results for both surface finish and form accuracy. It is concluded that overall performance of the process is very encouraging for producing glass moulds on the vertical CNC machining centre.

ABSTRAK

Tujuan utama kajian adalah menyelidiki keupayaan Pusat Pemesinan Pugak untuk menjana profail aspherik di atas acuan kaca. Rangsangan menggunakan mesin ini dalam kajian adalah untuk menjadikan proses pembuatan acuan kaca lebih mudahsuai berbanding dengan mesin khusus yang digunakan di dalam industri optik. Acuan kaca dicanai kasar dan dipelas dengan menggunakan empat roda pencanai intan yang mempunyai ikatan logam dan resin. Kedua-dua jenis ikatan digunakan diperingkat pencanaian dan pemelasan dengan saiz bijian 151µm dan 15µm masing-masing. Kajian secara teori dan ujikaji terhadap parameter pencanaian dan pemelasan, dan kelakuan bahan yang mempengaruhi keadaan mod separa mulur juga dibincangkan. Analisis merangkumi kinematik proses pencanaian, pencirian permukaan roda pencanai, mekanisma pembuangan bahan dan analisis kesahan sentuhan roda pencanai dengan permukaan acuan kaca juga diterangkan. Analisis kedalaman pemotongan mengesahkan bahawa keberkesanan sentuhan antara permukaan roda pencanai dan acuan mempunyai perhubungan parametrik dalam proses pencanaian. Sementara teknik analisis imej telah digunakan secara berkesan bagi melihat topografi roda pencanai dan permukaan canaian. Keputusan ujikaji telah dibandingkan dengan sampel sediada dari industri dan kaedah penjanaan secara zon untuk menentukan prestasi setiap proses. Didapati bahawa roda pencanai ikatan resin menghasilkan kemasan permukaan dan ketepatan bentuk/profail yang lebih baik berbanding dengan roda pencanai ikatan logam dan dari kedua-dua sampel industri dan kaedah penjanaan secara zon semasa operasi mencanai kasar. Kawasan pemesinan separa mulur dapat ditemui dalam sampel yang dipelas. Keputusan mempelas bagi sampel dari industri didapati sangat menggalakan dan sangat hampir dengan keputusan sampel yang diperolehi dari ujikaji dalam kedua-dua pengukuran kekasaran permukaan dan juga ketepatan profail. Dapat disimpulkan bahawa prestasi umum proses penjanaan dan pemelasan bagi menghasilkan acuan gelas dengan menggunakan Pusat Pemesinan Pugak adalah sangat menggalakkan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFM	-	Atomic force microscope
Al_2O_3	-	Aluminium oxide or alumina
ANOVA	-	Analysis of variance
a_p, a_e, a	-	Wheel depth of cut or in-feed
b	-	Cutting width, wheel width of cut, width of platelet
CBN	-	Cubic boron nitride
CCD	-	Charge-couple-device, central composite design
CD	-	Compact disc
CNC	-	Computer numerical control
CVD	-	Chemical vapour deposition
d_c	-	Critical depth of cut
DVD	-	Digital versatile or video disc
%E	-	% Error
E, *E*	-	Young's modulus, mean percentage error
$e \ldots e_i$	-	Percentage error of martensite on the individual image
ELID	-	Electrolytic In-Process Dressing
f, f	-	feed
F_c, F_H	-	Tangential cutting force
FEPA	-	Federation of European Producers of Abrasives
F_f	-	Feed cutting force
F_n, F	-	Normal cutting force
GIF	-	Graphic Interchange Format
H	-	Hardness of material
He-Ne	-	Helium-Neon
HK	-	Knoop hardness

h_{max}	-	Grit depth of cut
IC	-	Integrated circuit
K_c, K_{IC}	-	Fracture toughness
LCD	-	Liquid crystal display
LSI	-	Large scale integration
PV	-	Peak to valley
R	-	Tool nose radius
R_1, R_2	-	Lens radius
Ra	-	Arithmetic mean roughness value
r_c	-	Cutting ratio
R_{max}	-	Maximum individual peak to valley height
Rt	-	Roughness parameter
SEM	-	Scanning electron microscope
SiC	-	Silicon carbide
SPDT	-	Single point diamond turning
t	-	Time
tc	-	Critical thickness of cut
u	-	Specific energy
V_c, V_s	-	Cutting speed
V_{gw}	-	Cutting speed of grinding wheel
V_{ft}, V_{wp}	-	Table or work speed
W_a	-	Waviness height
W_{max}	-	Waviness parameter
WC	-	Tungsten carbide
W_{sm}	-	Waviness spacing
x%	-	Percentage of carbon at eutectoid point
y_c	-	Average depth of subsurface damage
y_i	-	Percentage of ferrite or pearlite
Z_{eff}	-	Damage transition line

Greek letters

μm	-	Micrometer, micron
ρ	-	Density
α	-	Thermal expansion coefficient
ϕ	-	Shear angle
γ	-	Rake angle
κ	-	Approach cutting edge angle
μ	-	Coefficient of friction
λ	-	Wave length
θ	-	Angle of tilting
Δf	-	feed / grain

LIST OF APPENDICES

CHAPTER 1

RESEARCH OVERVIEW

1.1 Introduction

For an astonishingly large number of people in poor countries, uncorrected vision prevents them from doing the things some of us take care for granted, like reading street signs or comparing advertisements to decide which market has the best price. According to World Health Organization, as many as billion peoples need vision correction but will never get it. Eyeglasses are scarce in developing nations because they cost too much for the average person, some time more costly than average monthly income, causing just few peoples qualified to diagnose eye problems and then provide the proper corrective lenses. In addition to this today, the optical industry requires aspheric optics not only for the visible spectrum, but also for high power and short wavelength radiation (eg X-rays, etc). At these wavelengths, a great necessity exists for aspheric surfaces on brittle materials, presenting the challenge of producing such complex optics as quickly as possible and at the lowest possible cost. This research is mainly dedicated towards the efforts for manufacturing the optical lenses with the use of general purpose vertical machining centre to avoid the dependency on dedicated ultraprecision machining centres. The present trend of the researchers and industrial practice was studied to identify the requirements for flexible and less costly manufacturing of optical lenses. The lens manufacturing could be the new horizon for small and medium scale industries if they could manufacture optical lenses with their existing setup. The final outcome of the research could be useful to convince such medium scale industries to step in optical lens manufacturing.

1.2 Research Background

Options for machining brittle materials like glass or silicon have always been scares. Cutting tools for the machining of glass are limited. Diamond is the only cutting material which has been used effectively for machining glass. The use of diamond for cutting glass can be found back in centuries as an example. For instance, optical lenses are manufactured under different precision machining levels and generally it can be sub divided into diamond turning and diamond grinding.

However, advances in the precision machining of brittle materials have led to the discovery of a "ductile regime" of operation in which material removal is by plastic deformation. Fracture mechanics predicts that even in brittle solids, material can be removed by the action of plastic flow, as is the case in metal, leaving crack free surfaces when the removal process is performed at less than a critical depth of cut (Puttick *et al.,* 1989). It means that under certain controlled conditions, it is possible to machine brittle materials like ceramics and glass using single or multi point diamond tools so that material is removed by plastic flow, leaving a smooth and crack-free surface. The diamond turning of germanium by Blackley and Scattergood (1991), diamond turning of silicon by Yan *et al* (2002), and diamond grinding of BK-7 glass by Bifano *et al*. (1991) using expensive ultra-precision machine tools have demonstrated how ductile streaks can be generated on hard, brittle materials when they are machined in a ductile mode. It has been reported that almost 100% ductile mode machining is possible when machining hard materials using a well defined geometry of single point single crystal diamond tools on a rigid ultraprecision turning machine (Venkatesh *et al.,* 1995). Instead of fully ductile mode, partial ductile mode grinding is possible when grinding hard and brittle materials on conventional Computer Numerical Control (CNC) machining centre using diamond cup wheels. Previous studies indicated that getting partial ductile streaks on the ground surface is a much better deal than a good surface finish as the former from polishing experience shows that saturation has taken place with the latter (Zhong and Venkatesh, 1995). Previous research work shows that in addition to ductile mode grinding and conventional fracture mode grinding, the intermediate mode of grinding, microcrack grinding, can also yield good results at a low cost. Microcrack grinding can also be described as partial ductile grinding. The main idea for using general purpose machine like Vertical Machining Centre (VMC) for aspharising is to reduce the cost of the final product.

In the case of grinding, finishing post processes like polishing and lapping are usually found to be more costly than other machining processes because of low their per unit volume of material removal, and so its use tends to be looked upon as a necessary evil. Partial ductile grinding is a more economical technology, where the ground surface can be directly polished without the intervention of the lapping process. The brittle materials can be ground in partial ductile mode on a CNC machining center. Polishing time can also be reduced substantially as the amount of ductile streaks can be increased in partial ductile grinding (Ong *et al*, 1994; Venkatesh *et al*, 1995). With conventional grinding machines, less than 90% ductile mode grinding is achievable and therefore the products require subsequent polishing (Zhong and Venkatesh, 1995).

1.3 Problem Statement

Researchers and manufacturers have put in a lot of efforts achieving low tolerances, better surface finish, and lower subsurface damage at reduced cost. In order to reduce the total manufacturing time, it is preferable to obtain better milled (rough ground) surfaces, even if it takes a little longer milling time, and to reduce the polishing time and subsequently product cost. Various problems reported by researchers and industry for producing aspheric lenses are as follows:

a) Uneconomical ultraprecision machining

It has been reported that ultraprecision as well as conventional grinding has been used to machine various profiles on hard and brittle materials. An ultraprecise grinding machine, capable of producing nanometric relative movements between the distributed cutting edges and work is required for generating aspheric surfaces by grinding. Fully ductile mode grinding on these materials is feasible when using high rigid ultraprecision machines, which leads to no polishing but the process is found to be relatively too slow and too costly for the products requiring less precision like ophthalmic lenses. Conventional grinding has advantages over ultraprecision grinding with respect to machining cost factor, able to machine at higher material removal rate but at the marginal expense of form accuracy (Izman, 2004).

b) Need of low cost machining

Since grinding is the critical operation among the abrasive machining processes (lapping and polishing) for removing material from hard, brittle components, there is an obvious need to develop a low cost machining technique that can minimize the subsurface damages of hard, brittle materials during machining and at the same time generate abundant amount of ductile streaks on the eventual machined workpieces.

c) Need of flexible machining and less setup time

The industrial procedures to manufacture aspheric lenses are employing very simple but special purpose machines. These machines are mass production machines capable of giving continuous output. The flexibility of the production system is the main problem faced by the industry working with these machines. These machines require very long setup time for small change in lens design. Some time it is not at all possible for such machines to incorporate such design changes in the lens geometry. In addition to this, the machine meant for aspheric generation can not produce toroidal lenses if requirement arise.

d) Specialized manufacturing

The present trend of the general machine shops of mold manufacturers has not been diverted towards glass moulds and lens manufacturing. The reason behind this fact may be the highly classified technology for lens manufacturing and lack of knowledge for machining the brittle materials like glass on general industrial platform.

1.4 Objective of the Study

The objective of the research is as follows:

1. To propose a new method of generating aspheric surface on the glass mould using conventional vertical machining centre.

2. To evaluate the performance of new method in terms of form accuracy and surface finish.

3. To compare the new generation process with the industrial practice and zone generation method in both, grinding and lapping operations.

1.5 Significance of the Study

The main emphasize in this project has been given on the general purpose accessories which are easily available in the market at low cost. The lens making industries are using highly specialized purpose machines like LOH aspheric generators for making aspheric lenses. The grinding wheels used in these machines are also specially designed for the typical geometry of the lens. Little variation in the lens geometry takes considerable time to set these special purpose machines. In addition to this, the machine meant for aspheric generation can not produce toroidal lenses if requirement arise. Typical manufactured product that could be produced by this method is the surface of the glass mould to manufacture plastic Fresnel lenses. These lenses are having variety of applications; some require high degree of accuracy such as lenses in the mobile camera whereas other could be liberal in tolerance such as binocular lenses. The main idea of the research is to produce such general purpose lens application by using the general purpose machine for manufacturing.

1.6 Scope of the Study

The research was confined to the following limits:

1. The work material used was optical BK7 glass.

2. Grinding operation was carried out on a vertical machining centre.

3. Commercially available diamond cup grinding wheels with resin and metal bond were used in the study for grinding and lapping operation. Grit sizes of 15µm and 151µm were used in the experiment for lapping and rough grinding respectively.

4. Unigraphics NX2 was used to model the parabolic profile and to produce aspheric grinding path for aspheric surface generation.

5. Scanning Electron Microscopy (S.E.M) and Optical Microscopy were used to analyze the surface. Formtracer CH5000 along with Formpak profile analysis software was used for surface roughness and form analysis. Image analysis was done with KS300 and VideoTest V5 imaging software.

6. A special fixture was developed to hold the workpiece and to provide additional rotation axis through modification of existing rotary table.

1.7 Overview of the Methodology

The overall methodology used for the experimentation to achieve the above objectives is shown in Figure 1.1. The experiments planned involve the use of 151µm and 15µm grit size grinding wheels. The rough grinding and lapping operations are planned sequentially to generate aspheric surface on the glass moulds. The parameters for the grinding are planned in accordance with the industry and zone generation method for evaluating the process performance. The results obtained are compared with the industrial samples and zone generation method results. Detailed qualitative and quantitative analysis was planned to examine surface texture of the samples.

1.8 Organization of the Thesis

The new technique of aspheric surface generation is developed with use of general vertical machining centre. The capability of vertical machining centre is evaluated for optical lens manufacturing. This chapter begins with the background of the problem that covers the issue leading to the problem statement. This is followed by the problem statement, objective of the study, significance of the study, scope of the study, overview of the methodology and ends with the organization of this thesis. The second chapter gives broad view of the various parameters of the optical grinding process, covering basic lens geometry with the application of aspheric lenses, various material removal mechanisms in grinding,

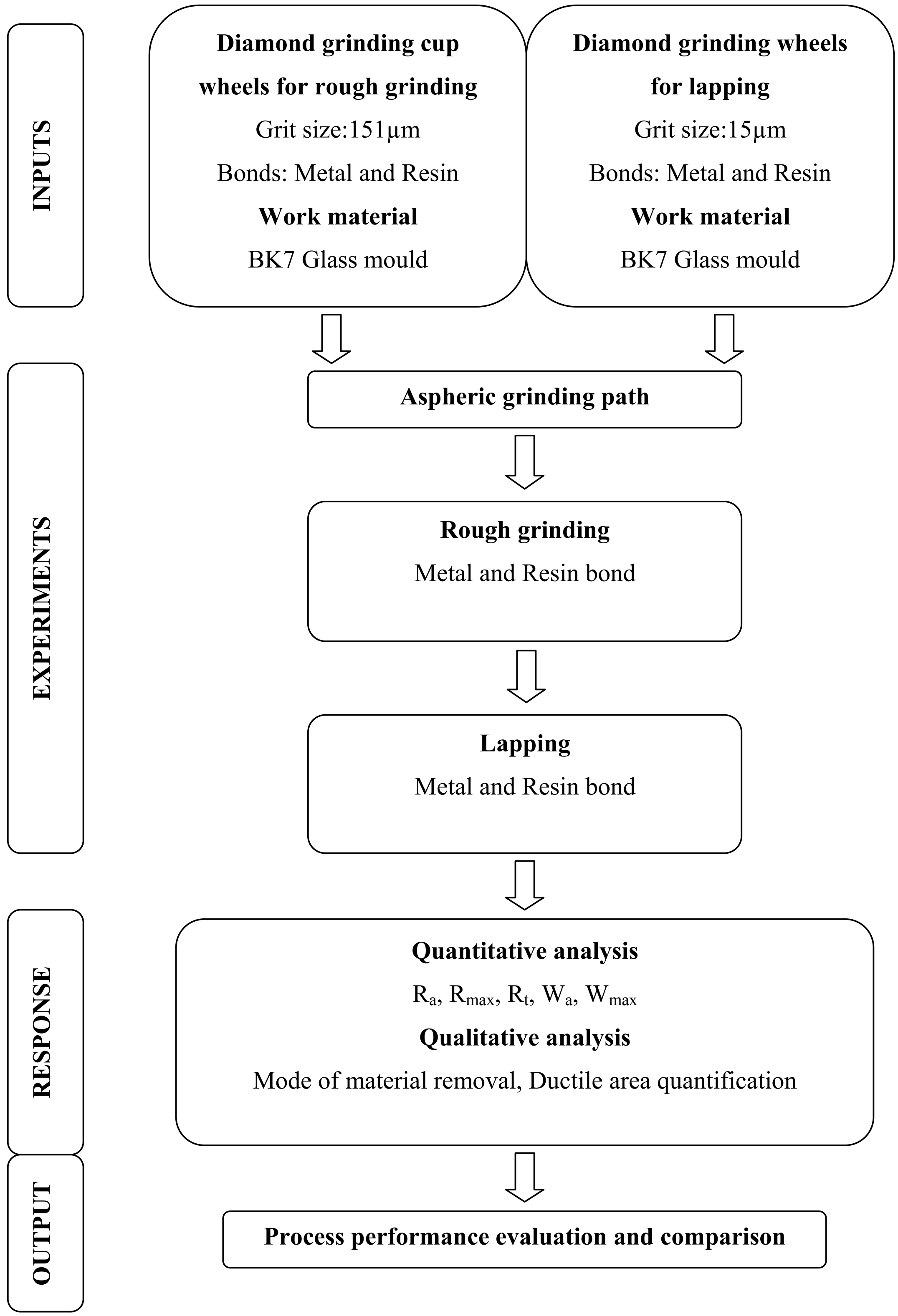

Figure 1.1: Schematic diagram summarizing the experimental approach

and type of grinding wheels used in optical industry. Third chapter narrowed to the various aspheric surface generation processes. The aspheric generation processes are divided in modification of conventional process and ultraprecision methods. Fourth chapter is describing the pre-experimental work and methodology. Detail plan of experiments is described in this chapter. Chapter five is the results of the experiments. Thesis ends with conclusions drawn for this research.

REFERENCES

Andrew, C., Howes, T.D. and Pearce, T.R.A. (1985). *Creep Feed Grinding*. Industrial Press. Inc. New York.

Anon. (1996). Schott Optical Glass Properties. Pocket Catalogue.

Anon. (2002). Tech Front: Defining Grinding Grains. Manufacturing Engineering. 6:24.

Anon. 2004 (online) available at http://www.wordiq.com/definition/Lens_(optics)

Aurich, J.C., Braun, O. and Wernecke, G. (2003). Development of a Superabrasive Grinding Wheel with Defined Grain Structure using Kinematic Simulation. *Annals of the CIRP*. 52(1): 275-280.

Bach, H. and Neuroth, N. (1995). *The Properties of Optical Glass*. Berlin Heidelberg: Springer-Verlag.

Bejamin, R. J. (1979). Diamond Turning at a Large Optical Manufacturer. *Optical Engineering.* 17(6): 574-577.

Berman, R. (1979). Thermal Properties, In: Field, J.E. (Ed.)., *The Properties of Diamond*. London: Academic Press Inc. 1-22.

Bifano, T.G. and Fawcett, S.C. (1991). Specific Grinding Energy as an In-Process Control Variable for Ductile-Regime Grinding. *Precision Engineering*. 13(4): 256-262.

Bifano, T.G., Dow, T.A. and Scattergood, R.O. (1991). Ductile-Regime Grinding: A New Technology for Machining Brittle Materials. *Trans. ASME. Journal of Engineering for Industry*.113: 184-189.

Bingham, R. G., Walker, D.D., Kim, D. H., Brooks, D., Freeman, R., and Riley, D. (2000). A Novel Automated Process for Aspheric Surfaces. *Proc. SPIE* 4093: 445-450

Blackley, W.S. and Scattergood, R.O. (1991). Ductile-Regime Machining Model for Diamond Turning of Brittle Materials. *Precision Engineering*. 13(2): 95-103.

Blake, P.N. and Scattergood, R.O. (1990). Ductile Regime Machining of Germanium and Silicon. *J. Am. Ceram. Soc*. 73(4): 949-957.

Bowen, D.K. and Wormington, M. (1994). Measurement of Surface Roughnesses and Topography at Nanometer Levels by Diffuse X-Ray Scattering. *Annals of the CIRP*. 43(1):497-500.

Chapman, G. (2003). Enabling Technologies for Ultra-Precision Manufacturing & Metrology. Technical talk presented on 18 January, 2003 at Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

Chen,W. K., Kuriyagawa, T., Huang, H. and Yosihara, N. (2005). Machining Of Micro Aspherical Mould Inserts *Precision Engineering*. 29(3): 315-323.

Clement, M.K.T. (1995). The Chemical Composition of Optical Glasses and its Influence on the Optical Properties. In: Bach, H. and Neuroth, N. (Eds). The Properties of Optical Glass. New York: Springer-Verlag.

Cook, N.H. (1966). *Manufacturing Analysis*. USA: Addison-Wesley Publishing Co. Inc..

Donaldson, R.D. (1979). Large Optics Diamond Turning Machine. Lawrence Livermore National Laboratory Report UCRL-52812 (Vol.1).

Dunnington, B.W. (1978). Diamonds for Abrasive Machining, Lapping, Polishing and Finishing. SME Technical Paper. MR78- 955:1-8.

Evans, C. (1989) *Precision Engineering: An Evolutionary View*. Cranfield Press, Bedford England.

Fang, F.Z. and Chen, L.J. (2000). Ultra-Precision Cutting of ZKN7 Glass. *Annals of the CIRP*.49(1): 17-20.

Fang, F.Z. and Venkatesh, V.C. (1998). Diamond Cutting of Silicon with Nanometric Finish. *Annals of the CIRP*. 47(1): 45-49.

Fang, F.Z., Venkatesh, V.C. and Zhang, G.X. (2002). Diamond Turning of Soft Semiconductors to Obtain Nanometric Mirror Surfaces. *International Journal of Advanced Manufacturing Technology*. 19: 637-641.

Fiedler, K.H. (1995). *Processing (Grinding and Polishing)*. In: Bach, H. and Neuroth, N. (Eds). The Properties of Optical Glass. New York: Springer-Verlag

Groover, M.P. (1996). *Fundamentals of Modern Manufacturing: Materials, Processes and Systems*. USA: Prentice-Hall International, Inc..

Hensz, R.R. (1969). Glass Grinding and Polishing. SME Technical paper. MR69-230: 1-11.

Herbert, S. (1972). A Marriage of Success. *Industrial Diamond Review*: 375-378, September 1972.

HMT. (1980). *Production Technology*. New Delhi: Tata McGraw Hill Publishing Company Limited.

Holz, R. and Sauren, J. (1988). Grinding with Diamond and CBN. WINTER Diamond and CBN Tools Catalogue. Ernst Winter & Sohn Diamantwerkzeuge GmbH & Co.

Horne, D.F. (1983). *Optical Production Technology*. 2nd Edition. Bristol: Adam Hilger Ltd.

Hung, N.P. and Y.Q. Fu. (2000). Effect of Crystalline Orientation in the Ductile-Regime Machining of Silicon. *International Journal of Advanced Manufacturing Technology.* 16: 871-876.

Inasaki, I. (1987). Grinding of Hard and Brittle Materials. *Annals of the CIRP*. 36(2): 463-471.

Inasaki, I., Tonshoff, H.K. and Howes, T.D. (1993). Abrasive Machining in the Future. *Annals of the CIRP*. 42(2): 723-732.

Izman, S. (2004). *Investigation into some aspects of partial ductile mode in wet and dry grinding of optical glass*, Universiti Teknologi Malaysia: PhD Thesis.

Izman, S., Venkatesh, V.C., Sharif, S., Mon, T.T. and Konneh, M. (2003). Assessment of Partial Ductile Mode Grinding of Optical Glass. Dojyo Workshop on. *High Speed Machining of Hard/Super Hard Materials*. Copthorne Orchid Hotel, Singapore: 121-126.

Izumitani, T., (1979). *Polishing, Lapping and Diamond Grinding of Optical Glasses*. Treatise on Material Science and Technology. Academic Press Inc., New York, 17: 116-149.

Kalpakjian, S. (1995). *Manufacturing Engineering and Technology*. 3rd Edition, New York: Addision-Wesley Publishing Company.

Kapoor, A. (1993). *A Study on Mechanism of Aspheric Grinding of Silicon*. Tennessee Technological University, USA: M.Sc. Thesis.

Kibbe, R.R., Neely, J.E., Meyer, R.O. and White, W.T. (1987). *Machine Tool Practices*. 3rd Edition. Singapore: John Wiley & Sons.

Kitajima, K., Cai, G.Q., Kumagai, N. and Tanaka, Y. (1992). Study on Mechanism of Ceramics Grinding. *Annals of the CIRP*. 41(1): 367-371.

Komanduri, R. Lucca, D.A. and Tani, Y. (1997). Technological Advances in Fine Abrasive Processes. Keynote Paper. *Annals of the CIRP*. 46(2): 545-596.

Konig, W. and Sinhoff, V. (1992). Ductile Grinding of Ultraprecise Aspherical Optical Lenses. *International Symposium of Optical Systems Design*. Berlin.

Konneh, M. (2003). *An Experimental Investigation on Partial-Ductile Mode Grinding of Silicon*. Universiti Teknologi Malaysia: Ph.D Thesis.

Koshy, P., Zhou, Y., Guo, C. and Chand, R. (2005). Novel kinematics for cylindrical grinding of brittle materials. *Annals of CIRP* 2005.

Kuriyagawa, T., Zahmaty M. and Syoji, K. (1996). A new grinding method for aspheric ceramic mirrors. *Journal of Materials Processing Technology*. 62: 387-392

Lawn, B.R. and Wilshaw, R. (1975). Indentation Fracture: Principles and Applications. *Journal of Material Science*. 10: 1049-1081.

Lawn, B.R., and Evans, A.G. (1977). A Model for Crack Initiation in Elastic/Plastic Indentation Fields. *Journal of Material Science*. 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. *Journal of American Ceramics Society*. 63: 574-581.

Lewis, T. G. (1962). Machining to millionths. *The Tool and Manufacturing Engineer*, 49(2)65-68.

Lim, H.S., Fathima, K., Kumar, A.S. and Rahman, M. (2002). A Fundamental Study on the Mechanism of Electrolytic In-Process Dressing (ELID) Grinding. *International Journal of Machine Tools & Manufacture*. 42: 935-943.

Lindberg, R.A. (1970). *Processes and Materials of Manufacture*. New Delhi: Prentice Hall of India Pte. Ltd.

Lindberg, R.A. (1990). *Processes and Materials of Manufacture*. 4^{th} Edition. New Jersey: Prentice Hall, Inc..

Lubarsky S.V., Sobolev V.G., Shevtsov S.E. (1990). Optical Surface Fabrication on Ultra Precision Machine. *Proc. SPIE* 1266:226-236.

Maldague, X. (2001). *Theory and practice of Infrared Technology for Nondestructive Testing*, John Wiley & Sons Inc, N.Y.

Malkin, S. (1989). *Grinding technology : Theory and Application of Machining with Abrasives*. England: Ellis Horwood Limited.

Marker, A.J. and Neuroth, N. (1995). Overview- Optical Glass: An Engineered Material. In: . Bach, H. and Neuroth, N. (Eds). The Properties of Optical Glass. New York: Springer-Verlag.

Mayer, J.E. and Fang, G.P. (1994). Effect of Grit Depth of Cut on Strength of Ground Ceramics. *Annals of the CIRP*. 43(1): 309-312.

McKeown, P.A., Carlisle, K., Shore, P. and Read, R.F.J. (1990). Ultraprecision, High Stiffness, CNC Grinding Machines for Ductile Mode Grinding of Brittle Materials, Infrared Technology and Applications. *SPIE* .1320: 301-313.

Meyer Arendt, J. R.. (1972). *Introduction to Classical and Modern Optics.* Prentice Hall, Inc. 103-104

Miyashita, M. (1989). Brittle/Ductile Machining. Fifth International Seminar on *Precision Engineering*. Monterey, CA. USA.

Nakasuji, T., Kodera, S., Matsunaga, H., Ikawa, N. and Shimada, S. (1990). Diamond Turning of Brittle Materials for Optical Components. *Annals of the CIRP*. 39(1): 89- 92.

Namba, Y. and Abe, M. (1993). Ultraprecision Grinding of Optical Glasses to Produce Super-Smooth Surfaces. *Annals of the CIRP*. 42(1): 417-420.

Namba, T., Kobayashi, H., Suzuki, H. and Yamashita, K. (1999). Ultraprecision Surface Grinding of Chemical Vapor Deposited Silicon Carbide for X-Ray Mirrors using Resinoid-Bonded Diamond Wheels. *Annals of the CIRP*. 48(1): 277-280.

Namba, Y., Wada, R., Unno, K. and Tsuboi, A. (1989). Ultra-precision Surface Grinder Having a Glass-Ceramic Spindle of Zero-Thermal Expansion. *Annals of the CIRP*.38(1):331-334.

Namba, Y., Yamada, Y., Tsuboi, A., Unno, K., Nakao, H. (1992). Surface Structure of Mn-Zn Ferrite Single Crystals Ground by an Ultraprecision Surface Grinder with Various Diamond Wheels. *Annals of the CIRP*. 41(1): 347-351.

Nicholas D. J and Boon, J. E. (1981). The Generation Of High Precision Aspherical Surfaces In Glass By CNC Machining *J. Phys. D: Appl Phys*. 14: 593-600

Ohmori, H., Kato, J., and Masaru, H. K. (1996) Ultraprecision Form Control of Aspheric Mirror with ELID Grinding. Spring-8 Annul Report: 218-219

Ong, N.S. and Venkatesh, V.C. (1988). Semi-Ductile Grinding and Polishing of Pyrex Glass. *Journal of Material Processing Technology*. 83: 261-266.

Pai, D.M., Ratterman, E. and Shaw, M.C. (1989). Grinding Swarf. *Wear*. 131: 329-339.

Pearce, C.A. (1972). *Silicon Chemistry and Applications*. London: The Chemical Society.

Puttick, K. E., Rudman, M.R., Smith, K.J., Franks, A. and Lindsay, K. (1989). Single-point Diamond Machining of Glasses. Proc. R. Soc. Lond. A426: 19-30.

Puttick, K.E. and Hosseini, M.M. (1980). Fracture by a Pointed Indenter on Near (111) Silicon. *J. Phys. D. App. Phys*. 13: 875-880.

Rao, P.N. (2000).*Manufacturing Technology*: *Metal Cutting & Machine Tools*. Tata New Delhi: McGraw-Hill Publishing Company Limited.

Reichenbach, G.S., Mayer, Jr. J.E., Kalpakcioglu, S. and Shaw, M.C. (1956). The Role of Chip Thickness in Grinding. *Trans. ASME*. 18: 847-850.

Rusell R G (1993) Comparison Of Metal And Resinoid Bonded Grinding Wheels With Various Grit Sizes In The Aspheric Surface Generation Of Silicon Lenses. Tennessee Technological University, USA: M.Sc. Thesis.

Schinker, M.G. (1991). Subsurface Damage Mechanisms at High-Speed Ductile Machining of Optical Glasses. *Precision Engineering*. 13(3): 208-218.

Shafrir (2004). Diamond Tool Wear - Observation by Scanning Electron Microscopy (SEM). Practical Scanning Electron Microscopy and Advanced Topics. Opt 307/507

Shaw, M.C. (1969). *Metal Cutting Principles*. 3rd Edition. New Delhi: Oxford & IBH Publishing Co.

Shaw, M.C. (1972). *A New Theory of Grinding*. Mech. and Chem. Eng. Trans. Institution of Engrs. (Australia). MC8: 73-78.

Stephenson, D. A. and Agapiou, J.S. (1997). *Metal Cutting Theory and Practice*. New York : Marcel Dekker, Inc.

Subramaniam and Ramanath. (1991). *Principles of Abrasive Machining. Ceramics and Glasses*. Engineered Materials Handbook vol.4, ASM International, The Materials Information Society:316.

Suzuki, H., and Murakami, S. (1995) An ultraprecision grinding machine for non-axisymmetric aspheric mirrors *Nanotechnology* (6):152-157.

Tabor, D. (1970). The hardness of Solids. Proc. of the Institute of Physics, F. Physics in Technology. 1: 145-179.

Tabor, D. (1986). *Indentation Hardness and Its Measurement: Some Cautionary Comments*, in Micro-Indentation Techniques in Material Science and Engineering. ASTM STP 889. Eds. P.J. Blau and B.R. Lawn: 129-159.

Tan, C.P. (1990). *Aspheric Surface Grinding and Polishing of Thermal Imaging Materials*. Tennessee Technological University, Cookville, USA: M.Sc. Thesis.

Tonshoff, H.K, Egger, R., Longerich, W. and Preising, D. (1998). Superfinishing Ceramics. Manufacturing Engineering: 52-60.

Ukam (2004) Industrial Superhard Tools Catalogue, 2004

Van Ligten, R.F. and Venkatesh, V.C. (1985). Diamond Grinding of Aspheric Surfaces n CNC 4-Axis Machining Centre. *Annals of the CIRP*. 34(1): 295-298.

Venkatesh, V. C. and Zhong, Z. (1995). Semi-ductile Grinding and Polishing of Ophthalmic Asperics and Spherics. *Annals of CIRP*. 44(1): 339 - 342.

Venkatesh, V.C., Chandrasekaran, H. (1987). *Experimental Techniques in Metal Cutting*. New Delhi: Prentice-Hall of India Pte. Ltd.

Venkatesh, V.C., Fang, F. and Chee, W.K. (1997). On-Mirror Surfaces Obtained with and without Polishing. *Annals of the CIRP*.46(1): 505-508.

Venkatesh, V.C., Inasaki, I., Toenshof, H.K., Nakagawa, T. and Marinescu, I.D. (1995). Observations on Polishing and Ultra-Precision Machining of Semiconductor Substrate Materials. Keynote Paper. *Annals of the CIRP*. 44(2): 611-618.

Volker, S., (1992). Ductile Grinding Of Ultraprecise Aspherical Optical Lenses. *International Symposium Of Optical System Design.* Berlin, Germany.

Walker, D.D, Brooks, D., Freeman, R., King, A., McCavana, G., Morton, R., Riley, D. and Simms, J. (2001) First Aspheric Form and Texture Results From a

Production Machine Embodying the Precession Process. *Proc. SPIE* Vol. 4451: 267-276, Optical Manufacturing and Testing IV; H. Philip Stahl; Ed., Dec 2001.

Walker, D.D., Beaucamp, A.T.H., Bingham, R. G., Brooks, D., Freeman, R., Kim, S.W., King, A., McCavana, G., Morton, R., Riley, D. and Simms, J. (2002). The Precessions Process for Efficient Production of Aspheric Optics for Large Telescopes and Their Instrumentation. *Proc. SPIE* Astronomical Telescopes and Instrumentation Meeting, Hawaii. 4842: 73-84.

Walker, D.D., Beaucamp, A.T.H., Bingham, R. G., Brooks, D., Freeman, R., Kim, S.W., King, A., McCavana, G., Morton, R., Riley, D. and Simms, J. (2003). Precessions Aspheric Polishing:- New Results from the Development Program. *Proc. SPIE* 5180: 15-28, Optical Manufacturing and Testing V. H. Philip Stahl. Ed. Dec 2003.

Walker, D.D., Brooks, D., Freeman, R., King, A., McCavana, G., Morton, Kim, S.W. (2003). The 'Precessions' Tooling for Polishing and Figuring Flat, Spherical and Aspheric Surfaces. 11(8). *OPTICS EXPRESS 958.*

Walker, D.D., Freeman, R., McCavana, G., Morton, R., Riley, D., Simms, J., Brooks, D., and King, A. (2001). The Zeeko/UCL Process for Polishing Large Lenses And Prisms. *proc. Large Lenses and Mirrors conference*, UCL, March 2001, pub. SPIE: 106-111.

Winter, (1996). Diamond Tools for Machining Precision Optical Glass, Spectacle Lenses and Technical Glass Components. Ernst Winter & SOHN Diamantwerkzeuge GmbH & Co.

Xiangdong, L. (2000) Ultraprecision Turning Technology. SIMTech technical report. (PT/00/008/PM).

Xu, X., Yu, Y. and Huang, H. (2003). Mechanisms of Abrasive Wear in the Grinding of Titanium (TC4) and Nickel (K417) Alloys. *Wear.* 255: 1421–1426.

Yan, J, Syoji, K., Kuriyagawaa, T. and Suzuki, H. (2002a). Ductile Regime Turning At Large Tool Feed. *Journal of Materials Processing Technology*. 121: 363–372.

Zhong, Z. and Venkatesh, V.C. (1995). Semi-Ductile Grinding and Polishing of Ophthalmic Aspherics and Spherics. *Annals of the CIRP*. 44(1): 339-342.

APPENDIX A
List of Publications and Awards

[1] Venkatesh, V.C., Izman, S., Vichare, P.S., Mon, T.T., Murugan, S.,(2005) The Novel Bondless Wheel, Spherical Glass Chips And A New Method of Aspheric Generation, *Int. J. of Mat. Proc. Tech*. Vol. 167 :184-190.

[2] Venkatesh, V.C., Izman, S., Vichare, P.S., (2005) Development of a novel bondless diamond grinding wheel for machining IC chips for failure analysis and for generation of aspheric surface, 55th *CIRP General Assembly*, Aug 2005, Antalya, Turkey.

[3] P.S. Vichare, S. Izman, V.C. Venkatesh, C. Woo, S. Murugan. (2005) Novel and flexible method of generating aspheric glass moulds, Manufacturing Systems Development - Industry Expectations. *Machine Engineering*, Vol. 5(3-4):45-59.

[4] V.C. Venkatesh, S. Izman, P.S. Vichare, C. Woo, S. Murugan (2005) New method of aspheric generation for manufacturing glass moulds on machining centres, *International Journal for Manufacturing Science & Technology*. Vol 8 (2). 29-34.

[5] Venkatesh V.C., Izman S., Mon T.T., Vichare P.S (2005) Critical depth of cut in vertical diamond grinding 24th All India Manufacturing Technology, Design and Research Conference (*AIMTDR*), Bangalore, India. pp. 128-133.

[6] Vichare P.S., Venkatesh V.C., Izman S., Rahim E. A., Hassan O., (2006) Flexible Process for Generating Aspheric Surface on the Glass moulds, *ICMM2006*, Kuala Lumpur, Malaysia.

[7] Venkatesh, V.C., Vichare, P.S., Izman, S., (2006) Kinematics Of Material Removal Process in Aspheric Surface Generation On Glass Moulds, *ICOMAST2006*, Melaka, Malaysia.

Gold Medal in association with Prof. Dr. V.C. Venkatesh and Dr. Izman at IPTA Research & Development Exhibition 2005, PWTC, October 2005. "Novel bondless diamond wheel (patent pending) for opto-electronic industries in association with Intel and Kennametal."