Pertanika J. Sci. & Technol. Supplement **12(2)**: 113 - 125 (2004)
ISSN: 0128-7680

Precision Grinding of Hard and Brittle Materials

V.C. Venkatesh, S. Izman, S. Sharif, T.T. Mon & M. Konneh
Department of Manufacturing & Industrial Engineering
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia, UTM Skudai, Malaysia
E-mail: venkates@fkm.utm.my

ABSTRAK

Dua teknik baru telah digunakan untuk mengkaji pembentukan jalur mod mulur semasa mencanai intan (proses utama) ke atas germanium, silicon dan kaca untuk membantu proses sekunder penggilapan. Dalam teknik pertama, permukaan aspherik telah dihasilkan atas Ge dan Si pada kelajuan konvensional (5000 pus per min). Dalam teknik kedua pula, pencanaian pada kelajuan tinggi (100,000 pus per min) ke atas permukaan rata kaca dan Si telah dilakukan. Ketepatan bentuk, kemasan permukaan dan jalur mod mulur dibincangkan dalam kertas kerja ini. Didapati bahawa roda intan ikatan resin menghasilkan jalur mod mulur lebih banyak berbanding roda intan ikatan logam tetapi sebaliknya roda yang terkemudian dapat menghasilkan ketepatan bentuk permukaan yang lebih baik. Permukaan canaian berlutsinar diperoleh dengan lebih mudah atas Pyrex berbanding kaca BK7, dengan itu telah dapat menjimatkan masa penggilapan. Jalur mulur kelihatan dengan banyaknya atas germanium berbanding silikon. Kedua-dua teknik pencanaian baru ini telah dijalankan atas pusat pemesinan CNC.

ABSTRACT

Two novel techniques were used to study the formation of ductile mode streaks during diamond grinding (primary process) of germanium, silicon, and glass that aid the secondary process of polishing. In the first technique aspheric surfaces were generated on Ge and Si at conventional speeds (5000 rpm). In the second technique high speed grinding (100,000 rpm) of plano surfaces on glass and Si surfaces was carried out. Form accuracy, surface finish and ductile mode grinding streaks are discussed in this paper. It was found that resinoid diamond wheels gave more ductile streaks than metal-bonded wheels but better form accuracy was obtained with the latter. Transparent ground surfaces were obtained more easily with Pyrex rather than with BK 7 glass, thus necessitating very little time for polishing. Ductile streaks appeared in abundance on germanium rather than silicon. Both the novel grinding techniques were used on CNC machining centres.

Keywords: Grinding, diamond wheel, ductile streaks, polishing, Ge, Si and Glass, surface finish and form

INTRODUCTION

Silicon, germanium and glass have become strategic materials that are widely used to fabricate intricate components in microelectronics in the optical industry, and recently for micro-electro-mechanical systems (Hung and Fu 2000). However, these materials pose particular problems in creating precision surfaces due to their extreme hardness and brittle nature. Machining of these materials can result in surface alterations including rough surface, cracks, subsurface damage and residual stresses, which later can commonly be finished by lapping and/or polishing to meet high shape accuracy and low surface roughness requirements. In some instances, machining on these materials also becomes uneconomical due to short tool life and low material removal rate (Tonshoff *et al.* 1998).

Recent advances in manufacturing technology make it possible for brittle materials to be machined in ductile manner. According to fracture mechanics theory, brittle materials can be removed by the action of plastic flow, as in the case of metal, leaving crack-free surfaces when the removal process is performed at less than critical depth of cut (Blake 1988; Blackley and Scattergood 1991). Critical depth of cut concept was further investigated by other researchers such as Fang and Venkatesh (1998), Fang and Chen (2000), Yan *et al.* (2001) on various brittle materials. This concept has been found to work well when machining hard and brittle materials using single point diamond tool on a rigid ultraprecision machine. It has been reported that fully ductile mode surfaces with nanometric finish are possible when using this kind of machine but at the expense of time and cost as the feed rate and depth of cut used are very fine. Bulk material removal is hardly possible using ultraprecision machines; therefore this process becomes less favourable for generating complex surfaces. As such, grinding process continues to be the most viable method for generating complex surfaces like aspherics, spherics and torics. Studies have shown that fully ductile mode machining was not possible with diamond grinding due to difficulty to control grain depth of cut as the protrusion height of diamond grits are randomly distributed all over the wheel surface. Instead, partial ductile mode machining is feasible where minimum post-machining process is required if abundant ductile streaks are present. As explained by Konig and Sinhoff (1992), some of the flattened diamond grains that protrude at different heights on grinding wheel become critical depth of cut which causes plastic material flow during grinding, leaving the ground surface with massive ductile streaks.

Traditional methods of generating aspheric surfaces on glass have been time-consuming (Horne 1984). A novel technique was developed by Van Ligten and Venkatesh which brought about heavy material removal without affecting surface finish and profile (Van Ligten and Venkatesh 1985; Van Ligten and Venkatesh 1986). The authors were able to obtain surfaces, which satisfied ophthalmic conditions, but not those expected of precision optics. This technique was extended to germanium and silicon using both metal-bonded and resinoid-bonded wheels.

The second technique involving plano surfaces was used on glass and silicon on a set-up similar to high speed jig grinding. Resinoid and electroplated diamond wheels were used to get transparency on glass and high quality surfaces on silicon. Surface finish, form accuracy, and smoothness were analysed on a Form Talysurf, while surface integrity was studied on Scanning Electron and Atomic Force Microscopes. SEM and AFM pictures show material removal both by ductile grinding and by fracture. These results are discussed in this paper.

METHOD

Aspheric Generation

To remove material quickly and end up with the desired surface, the contact area between the grinding tool and the work piece should be as large as possible. Since only spheres and toroids permit the condition of full area contact, partial area contact, or line contact will be the best alternative. The use of a machine with a rotating tool suggests that the contact surface must be symmetrically rotational. In general, the shape of the work piece is not predictable, hence, the condition of the large contact area is put in jeopardy. Thus, the method was chosen based on a long line contact between the tool and the work piece during the first step of rough grinding. During the subsequent steps of lapping and polishing, the use of a flexible tool allows conformity between the work piece and the tool, approaching the original condition of a contact area.

Two cup-shaped identical size diamond-grinding wheels with metallic (D20/30 MIC-L50M-1/4) and resinoid (SD240-R1OO B69-6mm) bonding were used. The profile of the grinding edge is circular in this case, but not restricted to this shape, thus forming a toroid. The important feature is that the grinding surface shape is axially symmetrical. It is now possible to program the path of this tool on the CNC-machine such that it is in line (or arc) contact with the work piece as it cuts the desired shape on the glass.

To illustrate this, the grinding of a paraboloid is shown. The cup tool can be thought of as consisting of a collection of circles whose planes are perpendicular to the axis of rotation of the tool. When the paraboloid is intersected by a plane, as shown in *Fig. 1*, the common line is an ellipse. When the task is to cut a concave paraboloid, the tool must fit inside the paraboloid. Hence, the tool must have a diameter smaller than the shortest radius found on the ellipse of intersection of any plane intersecting the paraboloid. In the case of a paraboloid, the shortest radius of curvature on the eclipse of intersection is found when the plane contains the axis of symmetry of the paraboloid.

Any circle at the outer side of the tool can be contained in one of the planes intersecting the paraboloid. The angle that this plane makes with the axis of the parabolid can be adjusted such that the arc of the circle and that of the ellipse (see *Fig. 1b*) at d, differs in sag height no more than a preset tolerance. This condition will set a certain common arc length over which the difference in sag does not exceed a certain value, say 0.5 micrometers. Now the work piece can be rotated around line 1 in *Fig. 1a*. After completion of one revolution, the surface left on the glass workpiece will be a zone of the paraboloid, as indicated in *Fig. 1a*. Subsequently, the tool axis can be programmed to take a slightly different position relative to the axis of rotation of the work piece, as well as relative to the apex *P*, of the paraboloid. The sequence is then repeated to form a neighbouring zone of the one indicated in *Fig. 1a*.

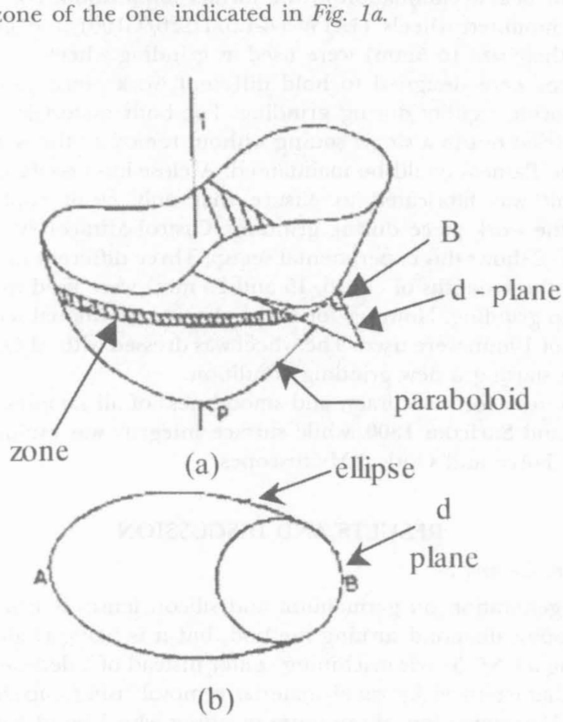


Fig. 1: A plane intersecting a paraboloid (a), in an ellipse (b)

Two 5-axis vertical CNC machining centres (Fadal and Deckel) (Venkatesh 1990) were programmed to perform these sequences continuously, until the paraboloid is completed. In this manner, a zone is ground during one revolution. While in cutting with a point tool, in principle, one line of the paraboloid is cut. It is thus clear that this method of grinding with the nearest arc-contact can complete the same surface faster than in the case of cutting with a point- tool. The thermal imaging materials used were monocrystalline germanium and silicon. Both blanks were polished after grinding. A special aluminium tool was developed. A felt cloth was glued to the spherical surface of this tool and a polishing paste of one micron alpha alumina was applied to it during polishing. The same set-up was used for polishing on the CNC machine.

Plano Grinding

The objective here is to grind plano (flat) surfaces, with the areas being quite small ($10x12mm^2$). Very high quality Si as thin as 1mm (wafer) and as thick as 10mm (lenses) and optical glass (BK7 and Pyrex) were used. An air-powered jig grinding unit (NSK Planet 1500) was attached to the vertical spindle of a MAHO CNC Milling machine to provide tool path movement in plano grinding. One advantage of using an air-driven low powered jig grinder is that it stalls when cutting forces exceed 10 Newton. The operating pressure of the Planet was set constant to 4 kgf/cm^2 throughout the experiment. The uneven cut surface on BK7 Schott glass workpiece that produced after diamond sawing was flattened prior to plano grinding using a resinoid cup wheel (SDC230 P100BW4-6). For rough grinding (flattening) and fine grinding operations the same grinding tool (grinding pin) was used for wafer applications and separately for the lens operation to avoid heat accumulation in the former application. For both work pieces, resinoid-bonded mounted wheels (1A1W-5-6-1.5/D126/C100) also known as grinding pins because of their size (ϕ 5mm) were used as grinding wheels.

Special fixtures were designed to hold different work piece geometry and at the same time to provide rigidity during grinding. For both materials, rough and plano grinding were carried out in a single setting without removing the work piece from the fixture so that the flatness could be maintained. A close-loop coolant system complete with filtering unit was fabricated to ensure that only clean coolant was supplied continuously to the work piece during grinding. Castrol Miracol 80 coolant with ratio 1:50 was used. *Fig. 2* shows this experimental set-up. Three different feed rates (5, 20 and 35mm/min) and three depths of cut (5, 15 and 25 mm) were used to grind silicon and BK7 glass in plano grinding. However for Pyrex glass, an additional feed of 2.5mm/min and depth of cut of 10mm were used. The wheel was dressed with Al_2O_3 bar (grade Nr.2) each time before starting a new grinding condition.

Surface roughness, form accuracy, and smoothness of all samples were analysed on a Form Talysurf and Surfcom 1800, while surface integrity was evaluated on Scanning Electron, Atomic Force and Optical Microscopes.

RESULTS AND DISCUSSION

Aspheric Surfaces on Ge and Si

Aspheric profile generation on germanium and silicon lenses is usually accomplished using the single-point diamond turning method, but it is being challenged by a novel technique utilizing a CNC 5- axis machining center instead of a dedicated machine. This new method is characterized by zonal material removal using cup-shaped diamond – grinding wheels. Determination of optimum grinding wheel bond type and grit size is of great importance in the success of this grinding method.

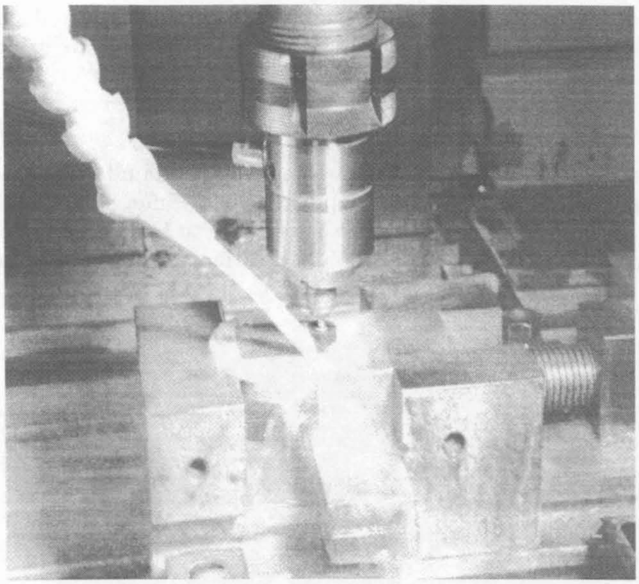


Fig. 2: High speed jig grinding of silicon and glass

Two grinding wheel bond types, metal and resinoid, each with three different grit sizes, 10-30 mm, 40-60 mm and 50-70 mm were used in generating aspheric surfaces using the grinding zone method. Surface texture and profile accuracy of each ground workpiece were measured and analysed using the Rank-Taylor-Hobson Form Talysurf. Also, the Scanning Electron Microscope was used to determine whether the material removal mode was predominantly fracture or ductile.

The resinoid-bonded wheel was superior for both Ge and Si. It could be redressed and trued, and commercial sizes are available. The metal-bonded wheel was made to our specifications and had considerable run out (0.279 mm) which could not be corrected. Better surface roughness values were obtained with both wheels for Si (Table 1). Si, however, was more difficult to polish and a lighter pressure had to be applied to prevent the felt from coming off. Thus, for the same time interval, Ge had a much better surface finish (Table 1). Polishing improved the form accuracy with Ge, but not with Si (Table 1). Both ductile and fracture modes of material removal were observed with both Si and Ge. *Fig. 3* shows some amount of ductile streaks on silicon and *Fig. 4* a massive amount

TABLE 1
Average roughness and form accuracy after grinding (G) and after polishing (P)

Type of Grinding Wheel	Ge		Si	
	Ra (mm)	Form Accuracy (mm)	Ra (mm)	Form Accuracy (mm)
Metal-bonded - G	0.722	4.16	0.583	6.03
Metal-bonded - P	0.057	2.867	0.123	6.490
Resinoid-bonded - G	0.706	1.845	0.123	1.898
Resinoid-bonded - P	0.045	1.238	0.191	2.433

of ductile streak on Ge. Better surface roughness, form accuracy, and smoothness can be obtained with a 5-axis CNC jig grinder, and also by dressing the grinding wheel by ductile mode as suggested by Miyashita (1988).

Plano Surfaces on Silicon and Glass

Results indicate that the surface roughness of precision ground Si improves with lower feed except in the case of the finest depth of cut of 5mm where higher feed rate improves the finish (*Fig. 5*). Ductile streaks also appear at higher feed rates (*Fig. 6*). *Fig. 7* is an AFM picture showing a mirror-polished surface of ground Si that had ductile streaks.

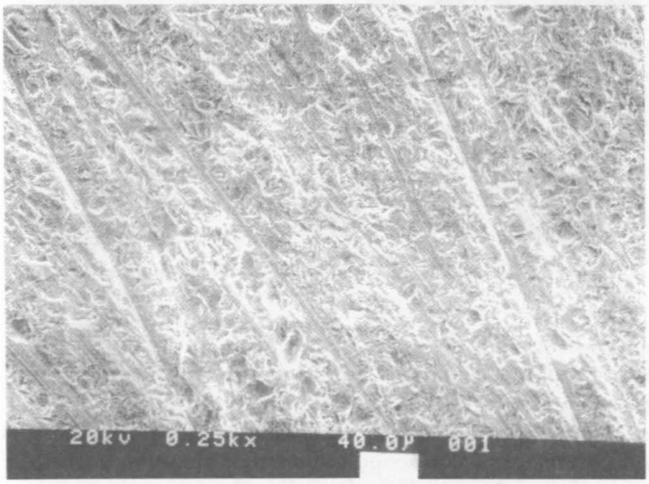


Fig. 3: Ductile streaks obtained on Ge during aspheric generation

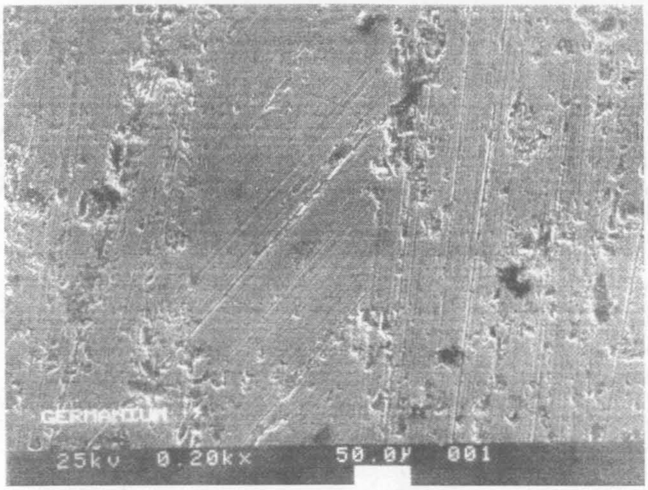


Fig. 4: Massive formation of ductile streaks on Ge during aspheric generation with a resinoid-bonded diamond wheel

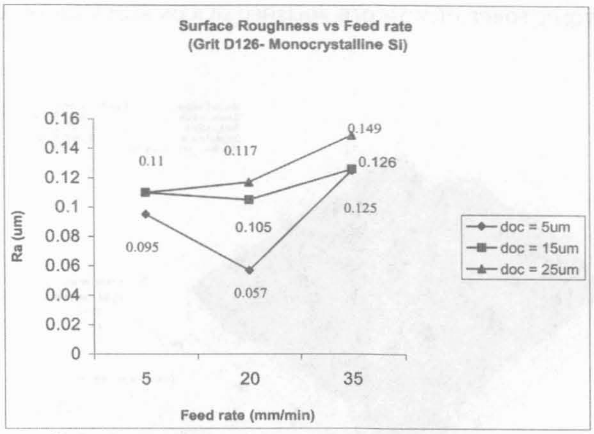
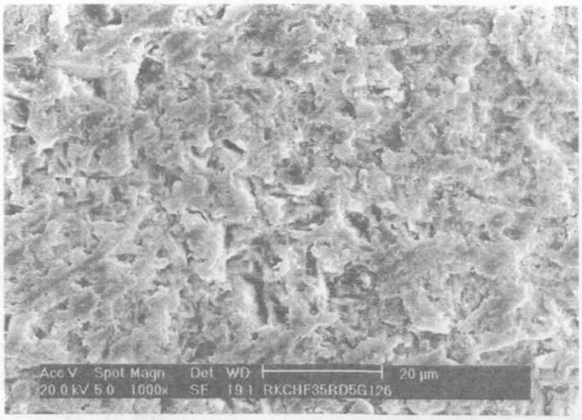


Fig. 5: Surface roughness obtained when silicon dies were precision ground at different levels of depth of cut and feeds

(a)



(b)

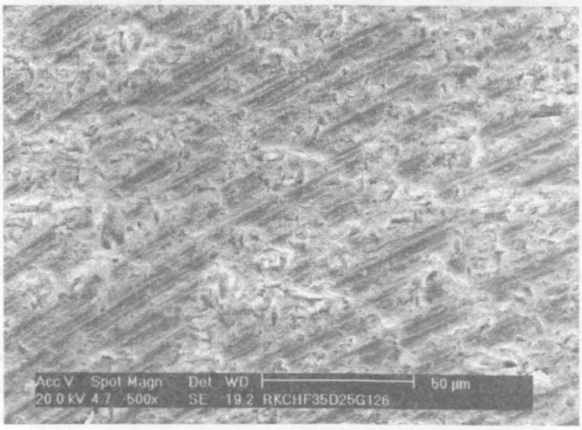


Fig. 6: SEM pictures of ground Si. The surfaces consist of (a) microfractures and (b) grinding streaks

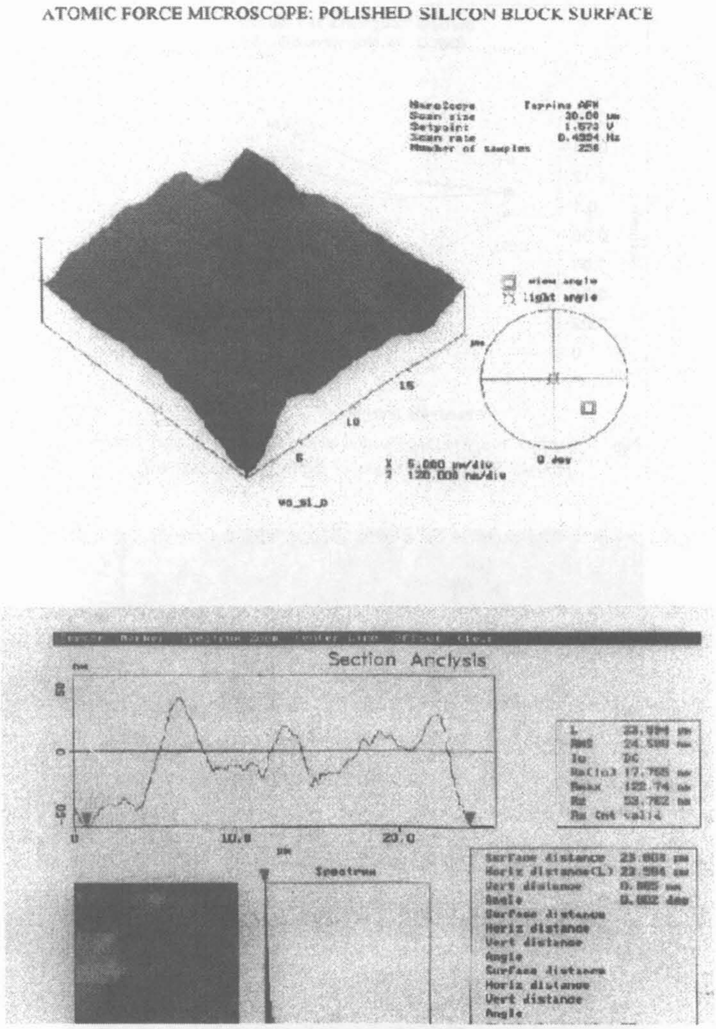


Fig. 7: Atomic force micrographs of the polished silicon surface that was ground with ductile streaks gave a surface finish of Ra = 17.755 nm and R_{max} = 122.74 nm

Although the 25 mm depth of cut gives relatively higher Ra values, ductile streaks are evident particularly at the 35 mm/min feed. Getting partial ductile streaks on the ground surface is a much better deal than a good surface finish as the former from polishing experience (*Fig. 8*) (Venkatesh and Zhong 1994) shows that saturation has taken place with the latter.

Generally on BK7 glass, surface roughness improved with decrease of feed rate as shown in *Fig. 9*. As can be seen from the graph, depth of cut of 25 mm provided the lowest Ra values at all levels of feed rate. Here again, it is seen that surfaces with ductile streaks obtained at a higher feed rate (*Figs. 10a* and *b*) with higher surface roughness are better than the surface with the better surface finish as the latter has reached saturation condition (Venkatesh and Zhong 1995). Displacement of material in the form

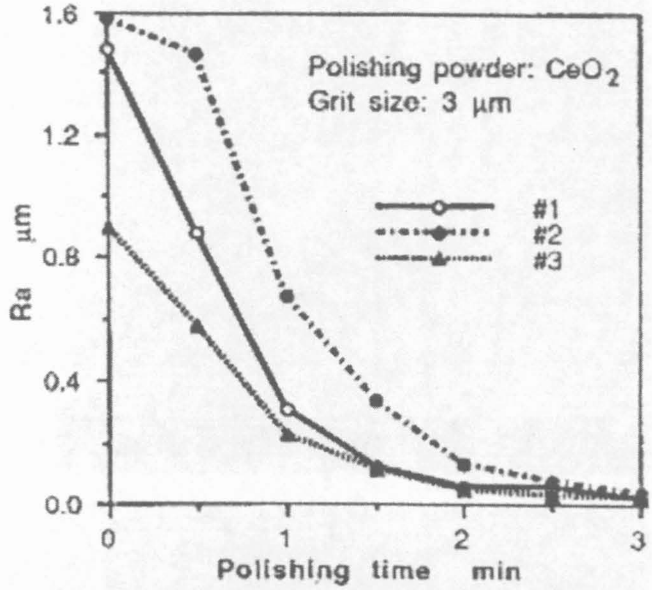


Fig. 8: Roughness value versus polishing time. Curve #1 with the largest amount of ductile streaks and maximum roughness achieved better surface finish faster than curve #3 which has the best surface finish (Venkatesh and Zhong 1995)

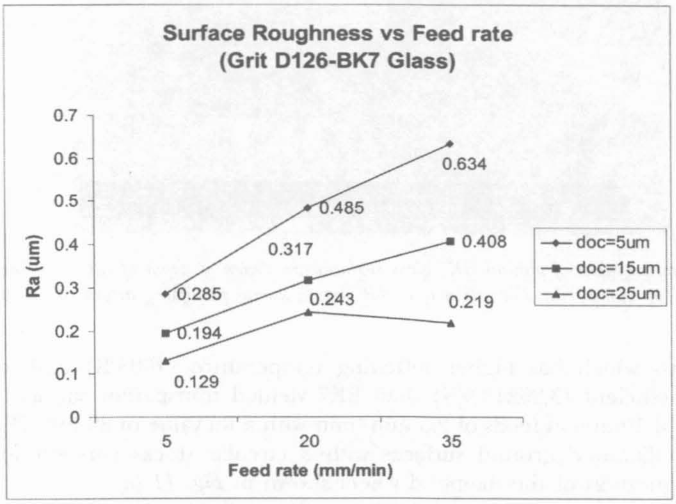


Fig. 9: Surface roughness obtained by plano grinding at different feeds and depth of cuts on BK7 glass

of chip on the ground surface in *Fig. 10b* shows evidence of plastic flow due to lateral ploughing action when critical depth of cut is reached. A similar chip has been observed at a higher feed 50 mm on a precision LOH aspheric generator (Venkatesh 2003).

(a)

(b)

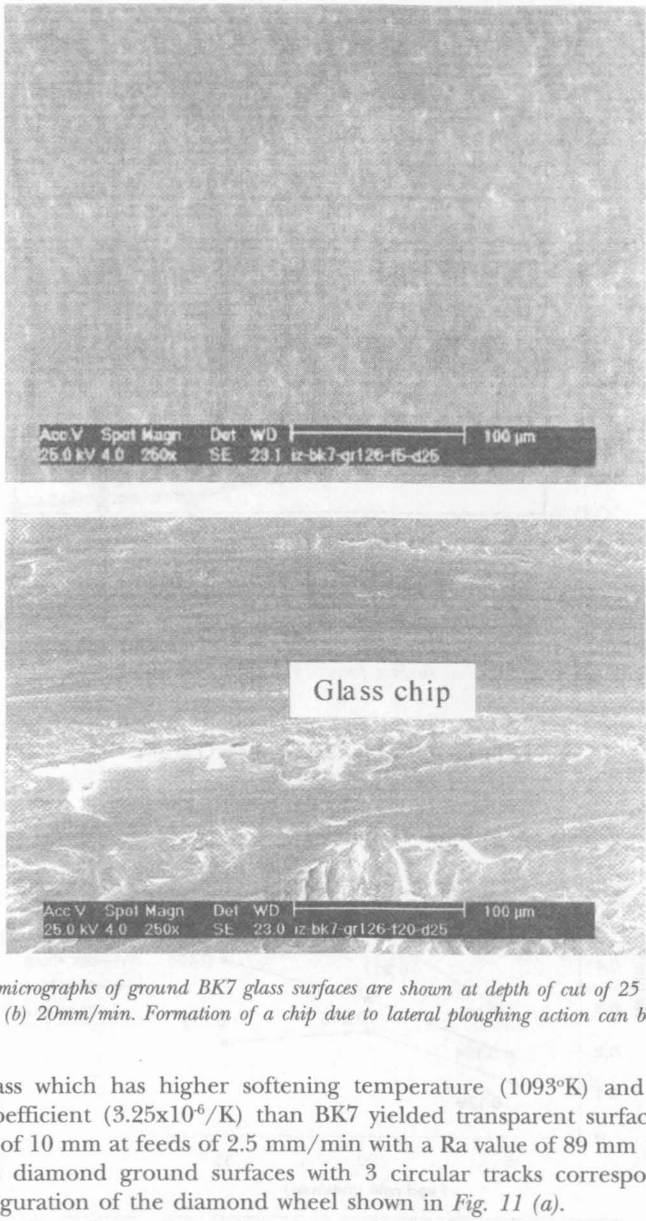


Fig. 10: SEM micrographs of ground BK7 glass surfaces are shown at depth of cut of 25 mm and feed of (a) 5 and (b) 20mm/min. Formation of a chip due to lateral ploughing action can be seen in (b).

Pyrex glass which has higher softening temperature (1093°K) and lower linear expansion coefficient ($3.25x10^{-6}$/K) than BK7 yielded transparent surfaces at a lower depth of cut of 10 mm at feeds of 2.5 mm/min with a Ra value of 89 mm (*Fig. 11*). *Fig. 11 (b)* shows diamond ground surfaces with 3 circular tracks corresponding to the conical configuration of the diamond wheel shown in *Fig. 11 (a)*.

This wheel is traditionally used for internal grinding and a slight conicity of the wheel end is to provide grinding relief. When used as a surface grinding wheel with a vertical axis the conicity gets more pronounced. It has been observed that the adjacent tracks get polished more easily than the central track in *Fig. 11(b)*, showing that the central track has reached a saturation stage seen in polishing curves (Venkatesh and Zhong 1995).

Using the wheel geometry and ground surface structure, the critical feed and depth of cut for partial ductile mode grinding can be determined. As clearly shown in *Fig.*

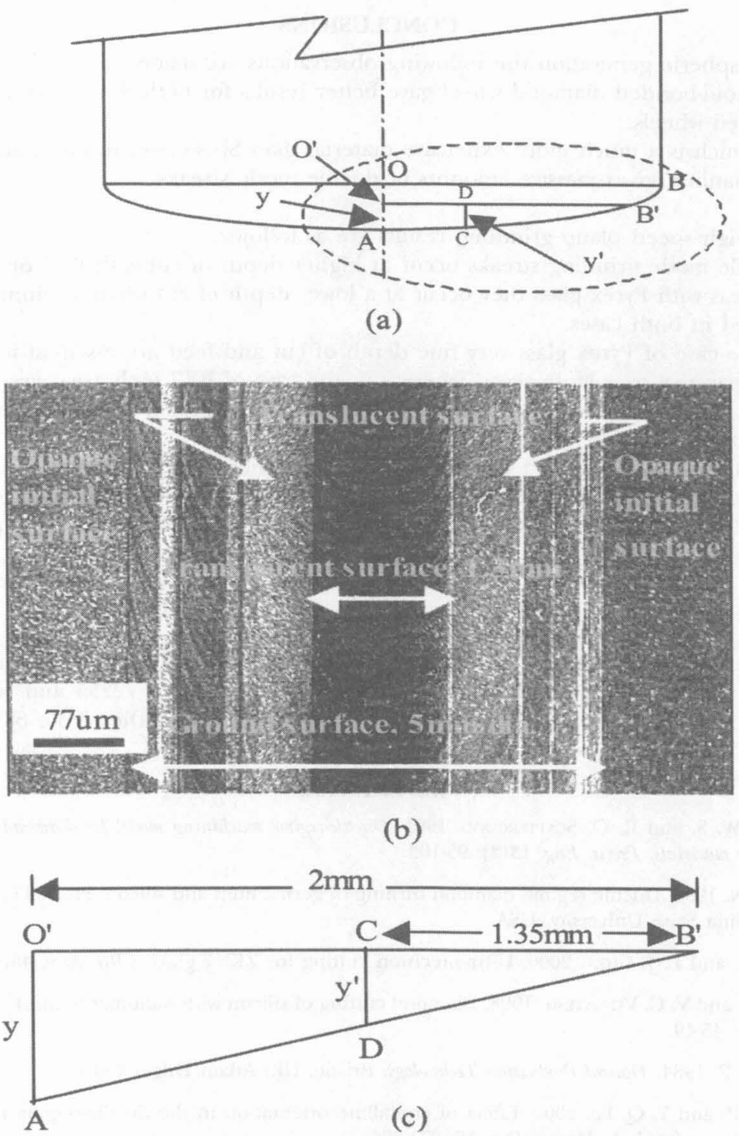


Fig. 11: (a) shows exaggerated conicity of grinding wheel (actual cone angle will be about 179.4°). (b) Plan view of ground surface whose diameter is less than wheel diameter, because depth of cut is less than y. The central part despite being fractured is transparent and the outer part is translucent despite the partial ductile streaks. (c) Enlargement of triangular area O'B'A in (a) for estimation of critical depth of cut (y')

11(c), depth of cut is higher at the central than the shoulder region. Substantial improvement in surface quality of the shoulder region indicates the existence of the critical depth (y'). Using the triangular cross section of the tip of grinding wheel, the critical depth of cut is about 7 mm where partial ductile mode grinding initiates and where fracture areas end (Mon 2003).

CONCLUSIONS

During aspheric generation the following observations are made:

1. Resinoid-bonded diamond wheel gave better results for both Si and Ge than metal bonded wheels.
2. Ge which is a much more expensive material than Si is easier to grind and polish. Germanium gives massive amounts of ductile mode streaks.

During high speed plano grinding, results are as follows:

1. Ductile mode grinding streaks occur at higher depth of cut with BK7 optical glass whereas with Pyrex glass they occur at a lower depth of cut when a minimum feed is used in both cases.
2. In the case of Pyrex glass very fine depth of cut and feed are essential for getting transparency over large areas, whereas in the case of BK7 such areas are scanty.
3. With silicon, considerable amount of ductile streaks are obtained at a higher depth of cut just like BK7 glass.
4. It has been observed with silicon, BK7 and Pyrex glass that larger amount of ductile streaks is preferable to a ground surface with better finish in order to get an excellent polish surface finish. This is due to saturation effect observed in polishing curves.

ACKNOWLEDGEMENTS

Sincere thanks are due to the Ministry of Science, Technology, and Environment, Malaysia for the IRPA Funding on Industrial Diamonds, Vote 72255 and to INTEL Malaysia, Penang for their research grant on Milling of Silicon Dies, Vote 68837.

REFERENCES

BLACKLEY, W. S. and R. O. SCATTERGOOD. 1991. *Ductile-regime machining model for diamond turning of brittle materials. Precis. Eng.* **13(2)**: 95-103.

BLAKE, P. N. 1998. Ductile regime diamond turning of germanium and silicon. Ph.D. Thesis, North Carolina State University, USA.

FANG, F. Z. and L. J. CHEN. 2000. Ultra-precision cutting for ZKN7 glass. *CIRP Ann.* **49(1)**: 17-20.

FANG, F. Z. and V. C. VENKATESH. 1998. Diamond cutting of silicon with nanometric finish. *CIRP Ann* **47(1)**: 45-49.

HORNE, D. F. 1984. *Optical Production Technology.* Bristle, UK: Adam Hilger Ltd.

HUNG, N. P. and Y. Q. FU. 2000. Effect of crystalline orientation in the ductile-regime machining of silicon. *Int. J. A. Manuf. Eng.* **16**: 871-876.

KONIG, W. and V. SINHOFF. 1992. Ductile grinding of ultra-precise aspherical optical lenses. *Int. Sym. Optical Systems Design,* Berlin.

KONNEH, M. 2003. An experimental investigation on partial ductile mode grinding of silicon. Ph.D. Thesis. Universiti Teknologi Malaysia, Johor.

MIYASHITA, M. 1988. *Ultraprecision in Manufacturing Engineering,* Berlin: Springer Verlag.

MON, T. T. 2003. Chemical mechanical polishing of optical glass subjected to partial ductile grinding. M. Eng. Thesis, Universiti Teknologi Malaysia, Johor.

TONSHOFF, H. K., R. EGGER, W. LONGERICH and D. PREISING. 1998. Superfinishing ceramics. *Manuf. Eng.* (Feb): 52-60.

VAN LIGTEN, R. F. and V. C. VENKATESH. 1985. Diamond grinding of aspheric surfaces on a CNC 4-Axis machining centre. *CIRP.Ann.* **34(1)**: 285-298.

VAN LIGTEN, R. F. and V. C. VENKATESH. 1986. Invention - mmachine to make aspheric surfaces. Patent Disclosure: National University of Singapore.

VENKATESH, V. C. and C. P. TAN. 1990. The generation of aspheric surfaces on thermal imaging materials on a 4-axis CNC machining centre. *Proc. Amer. Soc. Precis. Engineer's Annual Meeting,* p. 23-26. New York, USA: Rochester.

VENKATESH, V. C. and Z. ZHONG. 1995. Semi-ductile grinding and polishing of ophthalmic aspherics and spherics. *CIRP Ann.* **44(1)**: 339-342.

VENKATESH, V. C. 2003. Precision manufacture of spherical and aspheric surfaces on plastics, glass, silicon and germanium. *Current Science* **84(9)**: 1211-1219.

VENKATESH, V. C., S. IZMAN and M. KONNEH. 2000. Ultra-precision and high precision turning and grinding of brittle materials. *Proc. Indo-Japanese Seminar,* p. 99-104. Hyderabad, India: Asian Academy of Sciences.

YAN, J., M. YOSHINO, T. KURIAGAWA, K. SYOJI and R. KOMANDURI. 2001. On the ductile machining of silicon for micro-electro-mechanical systems (MEMS), opto-electronic and optical applications. *Mater. Sci. Eng. A* **297:** 230-234.