Precision manufacture of spherical and aspheric surfaces on plastics, glass, silicon and germanium

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This paper discusses the manufacture of aspheric and spherical surfaces in industries as well as in the universities with which the author is associated. Surfaces on plastics are produced by replicating them on glass moulds which, in turn, are replicated using ceramic moulds (for rotationally non-symmetrical lenses) or (for rotationally symmetrical lenses) ground on appropriate aspheric generators. The ceramic mould surfaces are generated on CNC milling machines. Rotationally symmetrical glass lenses were generated on both 4-axis and 5-axis CNC machining centres using both metal-bonded as well as resinoid-bonded cup grinding wheels. The same techniques were used for making lenses out of thermal imaging materials (silicon and germanium) where attempts to get semi-ductile mode of grinding were highly successful. The manufacture of spherical silicon lenses in industry is highlighted especially with respect to non-ductile regime grinding that increases polishing time. Results of surface texture and profile accuracy analyses using the Form Talysurf instrument are presented together with SEM pictures of the surfaces.

I was introduced to the fascinating topic of optics manufacturing by the late Van Ligten[1,2] during the period 1982–87 at the National University of Singapore. To him Horne's classic[3] on optics manufacturing was a Bible.

Optics can be divided into two categories: transmissive and reflective. Transmissive optics can be divided into three surface shapes and the associated machining operations are as below: (1) Flat optics – lapping and computer-controlled polishing; (2) Spherical optics – conventional machining; (3) Aspherical optics – diamond machining, computer-controlled polishing, nanofinishing.

Reflective optics comprise substrates with reflective coatings and mirror surfaces on silicon, germanium, aluminium and copper. A new development is free-form-optics that has evolved recently. Free-form-optics is considered to be the next frontier in the continuing development of single point diamond turning[4]. A free-form optical surface is one which is not symmetric about any axis. Multi-axis machining and metrology systems are required to manufacture these demanding optical components. Polaroid Corporation was a pioneer in mass produced free-form-optics for their instant camera products. They were forced to build their own 2-axis diamond turning lathe in the seventies, their own 3-axis coordinate measuring machine in the eighties and a 3-axis grinder in the nineties to produce free-form lens moulds.

In this paper, only manufacture of surfaces applicable for ophthalmic purposes (made of glass) and night vision (made of silicon and germanium) are dealt with. The tolerance for form is of the order of 8 μm but the surface finish for cosmetic reasons is of the order of 3 nm. Taniguchi[5] classified machining into four categories: normal, precision, high-precision and ultra-high precision as shown in Figure 1. Mechanical, electronic and optical parts made by these four machining processes are shown in Table 1.

Precision vs ophthalmic lenses

Optical surfaces are mainly required in two classes of products, viz. precision optics and ophthalmic optics. The distinguishing features between the two are qualitative and quantitative. Precision optics requires the highest accuracy in contour (Figure 2) of the optical surface. The spectacle-related optics are less stringent on contour but the demand on cosmetic quality of the surface is high. A number of problems exist in the production of precision optical elements and ophthalmic optical elements. The problems are further compounded when aspherics are preferred to spherical elements. The tolerance on vertical sag (see Figure 3) for ophthalmic lenses is ± 8 μm and on surface profile ± 4 μm for a lens of 70 mm diameter and 60 mm radius. For precision lenses the corresponding tolerances are one order of magnitude less.

Aspheric and spherical surfaces

Aspherics have the advantage of overcoming off-axis coma and aberration, which with spherical elements is corrected by increasing their numbers. A single aspheric can replace three spherical lenses[3] as shown in Figure 1. The maximum sag (difference) between an aspheric sur-

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face and spherical surface on a 70 mm blank having a radius of 60 mm shown in Figure 3 is 1.058 mm. The small difference ranging from 0 at the bottom to 6 μm within a diameter of 20 mm in the central and crucial region is extremely difficult to maintain. This makes aspheric lenses expensive compared to spherics.

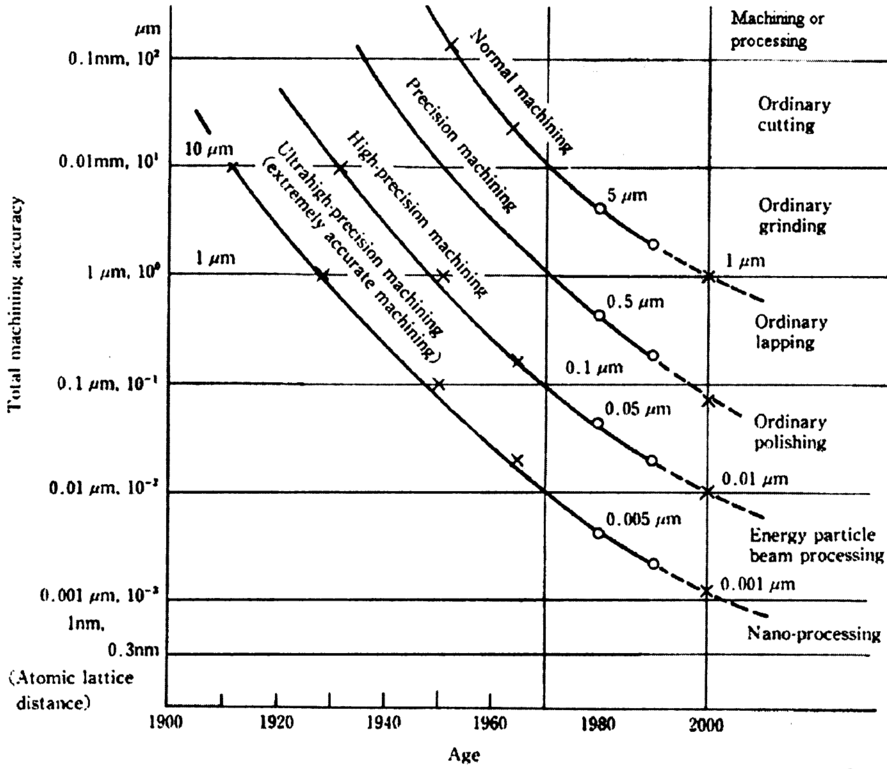

Figure 1. Machining progress in tolerances during the 20th century (ref. 5).

Table 1. Classification of precision products as a function of tolerances (ref. 5)

Tolerance (accuracy)	Mechanical parts	Electronics parts	Optical parts
200 μm	Normal machine and home-ware parts	General-purpose electric parts (switch, motor, connector)	Camera and telescope bodies
50 μm	General purpose mechanical parts (gear, thread), typewriter parts, engine parts	Package (electronic parts), micromotor, transistor, diode, magnetic head (tape recorder)	Camera shutter, lens holder (camera, microscope)
5 μm	Mechanical watch parts, accurate gears, threads machine tool bearings, ball screw, rotary compressor parts, shaver blade	Electric relay, resistor, condenser, disk memory, silicon wafer, TV colour mask, video head and cylinder	Lens, prism, optical fibre and connector
0.5 μm	Ball and roller bearings, precision drawn wire, flapper servo valve, gyro bearing, air bearing, precision die, roll thread die, ink jet nozzle	Magnetic head (video cassette recorder), magnetic scale, CCD, quartz oscillator magnetic bubble memory, IC, magnetron, thin film-pressure transducer, thermal printer head	Precision lens and prism, optical scale, IC exposure mask (photo, X-ray), laser polygon mirror, X-ray mirror, elastic deflection mirror
0.05 μm	Block gauge, diamond indenter, high-precision XY table, high-precision stamper and die, microtome cutter (diamond)	IC memory, electronic video disk, large-scale IC, microvacuum tube, TFT-LCD	Optical flat, precision Fresnel lens, optical diffraction grating, optical video disk (CD)
0.005 μm (5 nm)	Ultraprecision parts (plane, ball, roller, thread)	VLSI, super lattice (synthesis) thin films	Ultraprecision diffraction grating
Special feature	Shape (3-D) preciseness	Pattern (2-D) finenesss	Mirror surface roughness grating (1-D) accuracy

Over the years many new developments have taken place in optics manufacture but none as encouraging as the ductile machining concept that makes use of ultra-precision machining and the basic ideas are illustrated in Figure 4. Miyashita[6] has made a very fine analysis of the transition from conventional grinding to ductile mode grinding where the boundary between the two is known as micro-crack grinding (semi-ductile grinding). This is exemplified in Figure 4 where material removal rates (MRR) and abrasive grain size are also indicated[6]. From Figure 4, we can say that for semi-ductile machining the MRR is 10^{-2} mm^3/min, grain size 10^3 nm, and from our study $R_a = 0.7$ μm.

Materials

Glass

Glass is often called a supercooled liquid and is in a vitreous state. It is amorphous and therefore easy to polish[7]. Its main constituent is silica (60 to 70%) which is the glass former, together with modifiers consisting of oxides of calcium, sodium, potassium, barium and magnesium, with traces of arsenic and antimony. The optical glass used in our studies is crown glass supplied by Corning that has a refractive index of 1.5231. This glass is as yet difficult to turn into ductile mode but international efforts have had some measure of success with single crystal diamonds[8,9]. Our efforts to use a conventional CNC lathe for turning with a PCD tool have had reasonable success. Aspheric grinding however is no problem[1,10,11]. Zerodur glass is more difficult to polish than crown glass because it is harder and the passivation action during chemical mechanical polishing is less effective.

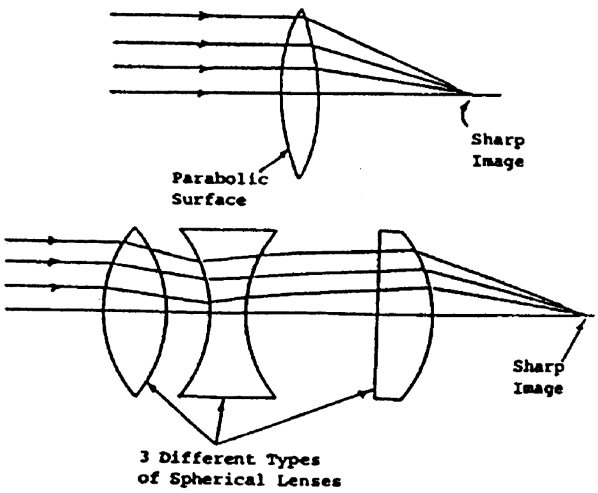

Figure 2. A single aspheric lens can do the job of three spherical lenses.

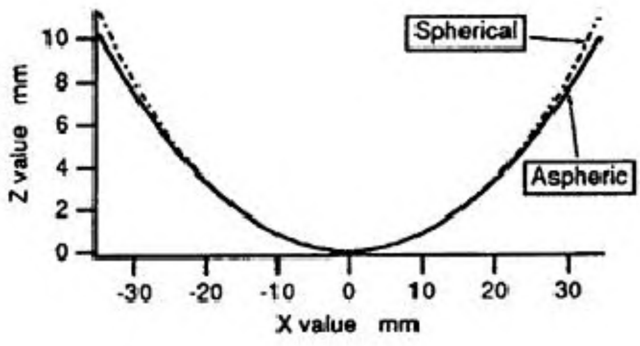

Figure 3. Vertical sag of a sphere and an asphere.

Plastic

The material used for plastic lenses is allyl diglycol carbonate, a thermosetting organic polymer, which is optically similar to crown glass. Plastic lenses cannot be turned, ground, or polished but have to be replicated in glass moulds. Plastic lenses have the following advantages: (i) cheap to manufacture through moulding route instead of grinding and polishing, (ii) relatively light weight and of non-brittle character, (iii) fairly good infra-red and ultraviolet transmittance.

Silicon and germanium

Thermal imaging materials like Si and Ge allow the transmission of infra-red radiation. They are used in optical systems to collect infra-red radiation from the source and to focus it on the surface of a detector. The primary requirement of an infra-red optical material is that it shall afford maximum transmission of infra-red radiation in the desired wavelength band. Smooth, uncracked surfaces are therefore important as light reflection or transmission depends on the integrity of the surface.

Silicon is a steel-gray cubic crystal with a high melting point and a high index of refraction. It has a high percentage transmission of incident radiation. It has a low thermal expansion coefficient and a high thermal conductivity. Silicon is more difficult to machine than germanium but is a much cheaper material and therefore a popular material for night vision lenses[1,10–15]. Germanium has a cubic crystal structure. It has a density more than twice that of silicon. It provides very good transmission of about 50% in the 2 to 15 micron range up to about 45°C. Germanium is easier to machine[12,13] but is expensive and therefore used for applications like small windows and filters.

This paper discusses both conventional and semi-ductile grinding of aspheric and spherical products and/or moulds for manufacturing plastic, glass, silicon, and germanium lenses.

Manufacture of aspheric plastic lenses

Manufacture of ceramic moulds for making glass moulds

One method of manufacturing plastic lenses with which we are associated uses glass moulds to form the lens. The method used is the classical replication technique[3] shown in Figure 5, but modified in their set-up for mass manufacture of ophthalmic lenses. During polymerization there is a 14% shrinkage of the plastic material. To accommodate this dimensional change, the mould is in two pieces forming the front and back surfaces of the lens. These pieces are held together with a pliable gasket material. For typical ophthalmic lenses, the mould surfaces are spheres or toroids that are readily shaped using conventional methods. These techniques are quick and inexpensive.

A relatively new type of lens known as progressive addition lens (PAL) is aspheric. It serves the function of a bifocal in that there is a distance-viewing region and a reading one. These two regions are smoothly joined in such a manner that this intermediate is useful for medium range viewing by presbyopes. Being smooth the lens is also cosmetically superior to bifocal lenses. Fortunately the lens is only critical in the distance and reading portions that are of spherical shape. The remaining area is less critical but must have an optical finish. This allows a simple method of mould making known as sagging. The mould making process uses a 6 mm thick, spherical glass blank made in the usual fashion and polished on both sides. In a separate step a ceramic block of 90% Al_2O_3 and 10% clay is diamond ground to the PAL topology on a Bostomatic numerical control milling machine[16]. The glass blank is placed upon the ceramic block. The temperature is raised to the softening point of glass. The ceramic material is chosen for an apparent porosity of 40%. Air is drawn through the block creating a pressure on the blank. In this way a tight control on the mould specification can be obtained.

The ceramic blanks are held in fixtures tilted at 20° mounted on the table of the Bostomatic CNC milling machine. The blanks remain stationary (Figure 6 *b*). The diamond wheel (Figure 6 *a*) that is used for machining the ceramic blanks has diamonds bonded together by a thin coating of Ni on Al–Si substrate. One diamond wheel is able to machine ten moulds in a single pass. Wear of the diamond wheel is shown in Figure 6 *c* before use and Figure 6 *d* after 10 moulds where one can observe the gradual depletion of the diamonds. Grinding high-density ceramics is relatively easy but low-density ceramics clog the wheel and cause abrasive wear of the bond.

Manufacture of glass moulds by grinding

Manufacture of the ceramic mould is competitive but making the glass mould from the ceramic mould by the sagging process involves time sometimes as much as an hour. Added to this is the fragility of the ceramic moulds that can easily break during handling.

Glass moulds were manufactured by fine grinding on a CNC Loh aspheric generator and then polished. The

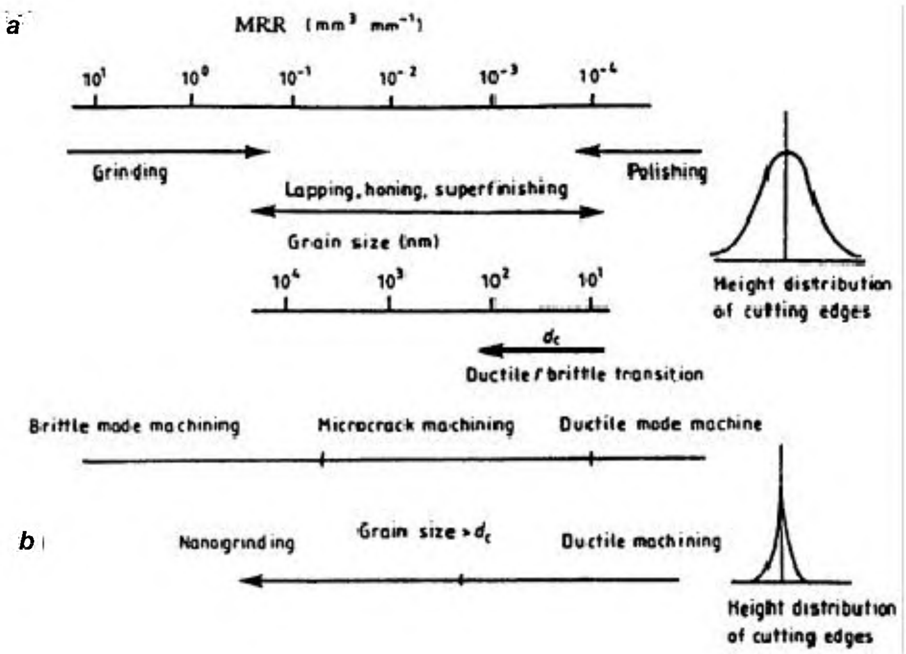

Figure 4. Conventional machining processes (***a***) versus nanogrinding process (***b***) (ref. 6).

variety in ophthalmic lenses is very high. With human beings who need to wear spectacles, very rarely is the power of one eye the same as the other eye. This huge variety in the assembly of gaskets containing the inner and outer glass moulds for making lenses necessitates the need for automation and this has been very successfully achieved.

An extensive SEM analysis as well as surface roughness, waviness and profile analysis were done by me. In Figure 7 *a* the feed mark of 0.1 mm in-feed is clearly visible whereas in Figure 7 *b* the feed marks (0.05 mm) are hardly visible. Figure 7 *c* which is an enlargement of Figure 7 *a* shows largely fractured areas. On the other hand, Figure 7 *d* – an enlargement of Figure 7 *b* – shows lots of desirable ductile grinding streaks. Research has shown that for brittle materials to have 99% ductile mode machining (1% fracture), one must use an in-feed rate of 1.5 nm/rev and a depth of cut less than[6] 1 μm. These conditions are available only with ultra-precision machine tools and with very special grinding wheels, both of which are expensive. The economics of ultra-precision machining needs to be presented after a thorough analysis, in order to lure industries into these green pastures. Semi-ductile (semi-fracture) looks a more attractive alternative to industries as both machine tools and grinding wheels are reasonably priced. The surface roughness and waviness results also provided a pleasant surprise, with the waviness value (0.7204 μm) being less than the roughness value (0.8057 μm). This is a clear indication of a very rigid machine tool and a very stiff spindle-wheel system. It is possible to increase the semi-ductile region by experimenting with the diamond wheel, for example with very fine grit size, and/or high concentration, the other possibility being the use of resinoid wheels.

Manufacture of aspheric glass lenses

Aspheric generator

This technique has been described in the previous section.

CNC machining centre

Four-axis machine: The 4-axis method uses the conventional 3-axis vertical milling CNC machine with a tilting table, incorporating an independent rotary table (without CNC control) for the grinding process. This method provides a continuous rotary action of the workpiece during the grinding process and a dwell of 6 s for spark-out is incorporated at every zone of the grinding process. This method has the advantage of providing a fairly constant wear of the grinding wheel around the workpiece while grinding, because of the constant rotation of the workpiece provided by the independent rotary table axis[1,10,11].

Five-axis machine: The 5-axis method uses a 3-axis conventional CNC machining centre that incorporates a tilting rotary table and the rotary action of the rotary table. The motion of the individual axis is dependent on one another. This method does not provide a continuous rotary action of the workpiece throughout the whole grinding process and a dwell of 12 s for spark-out is incorporated at every zone. This process also does not provide a constant wear of the grinding wheel around the workpiece, because the workpiece only rotates after an initial depth of cut has been made on the workpiece. This results in the tool wearing out as it approaches the end of a complete rotation of the workpiece[11–14]. The 5-axis method is, as expected, more costly due to the fact that the spark-out time is longer because of the slower rota-

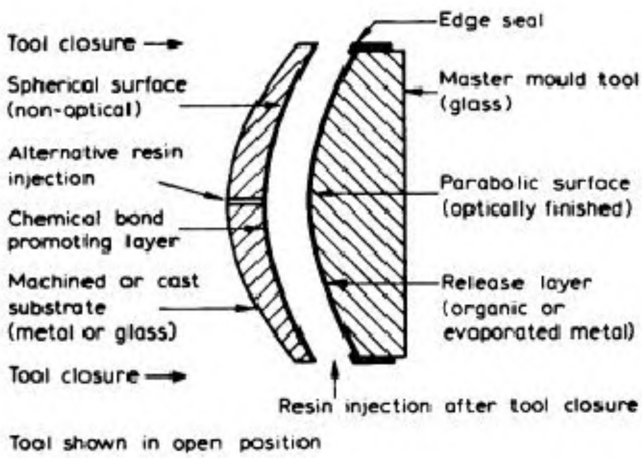

Figure 5. Optical replication schematic representation (ref. 3).

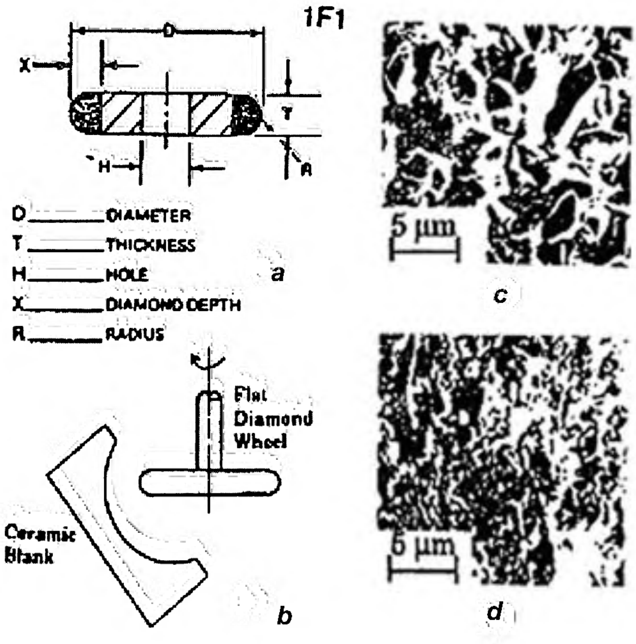

Figure 6. (***a***) Diamond wheel, (***b***) machine tool-grinding wheel setup, and wheel (***c***) before use and (***d***) after grinding 10 moulds.

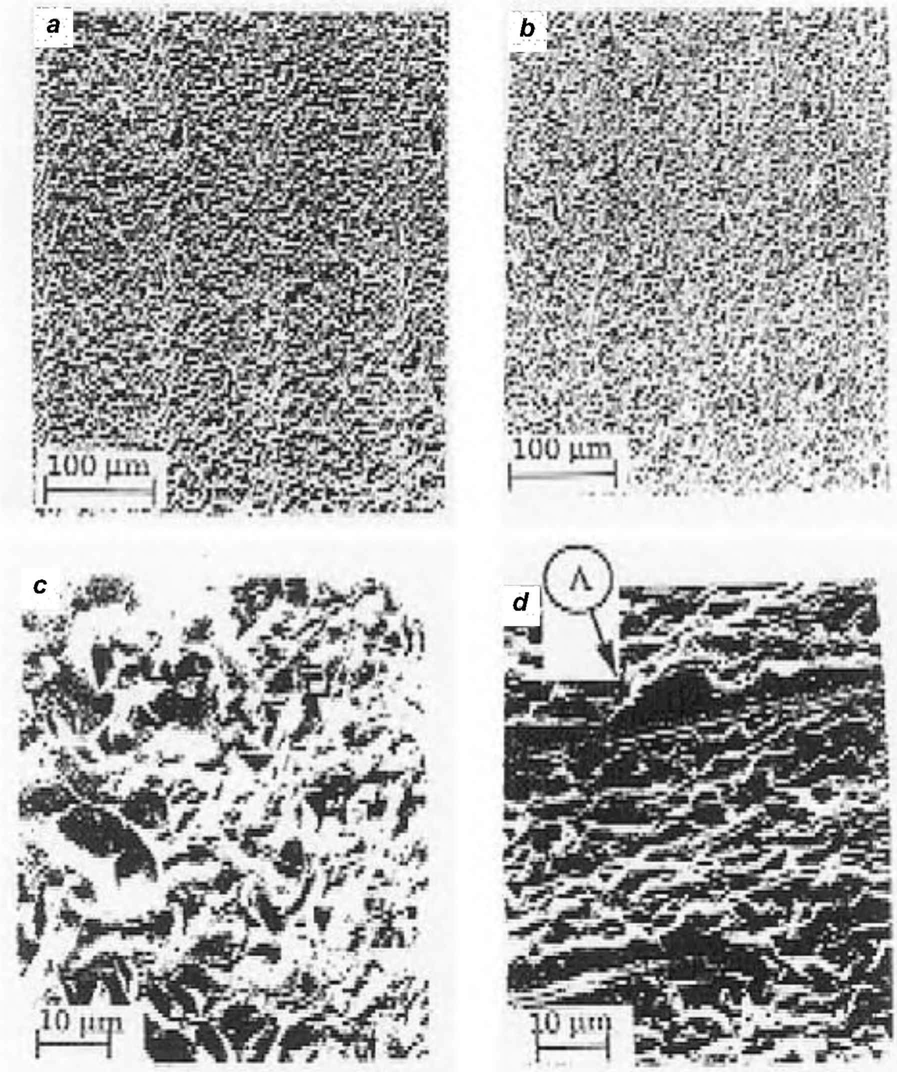

Figure 7. Ground glass mould surfaces indicate (***a***) clearly the feed mark of 0.1 mm and (***b***) barely the feed mark of 0.05 mm. (***c***) An enlargement of (***a***) shows severe fracture caused by material removal through indentation, and (***d***) an enlargement of (***b***) shows desirable ductile streaks with chip formation (A), indicating cutting action.

tional speed of the fifth axis on the CNC machine. However, the surface roughness and waviness values are smaller than the 4-axis method due to its slower workpiece feed rate during the grinding process. There also exists a slight depression on the initial cut of the workpiece at its apex for the 5-axis method. This is because the workpiece rotates only after an initial cut has been made by the grinding wheel. The wheel wears and when the workpiece completes its rotation, the wear on the grinding wheel causes an uneven layer of material removal on the workpiece, resulting in the formation of a depression.

Metal-bonded and resin-bonded diamond wheels

A 2FF2 Norton cup-shaped diamond wheel was selected and its assembly is shown in Figure 8. The profile of the grinding wheel is circular and its surface shape is axially symmetrical, making it possible to program the tool such that it makes line contact with the workpiece as it cuts the desired shape. Metal-bonded wheels were initially used as these do not wear easily on radius work or on small areas of contact. Subsequently resinoid bonded wheels were used quite successfully (Figure 9). SEM pictures of the metal and resin bonded wheels are also shown in Figures 8 and 9 respectively. With metal-bonded wheels the diamonds stand out whereas with resin-bonded wheels they are more enveloped by the bond that is compliant but opens out with grinding temperature.

The general equation of a parabolic is given as $Y = PX^2$, where P is the parabolic parameter. The results of parabolic parameters for the two different types of wheels and methods are shown in Figure 10. Metal-bonded wheels gave better surface roughness. Resin-bonded wheels produced brighter surfaces with more ductile streaks[15]. The wheels are not available in the 2FF2 design. This makes them less stiff. The effect of 4 and 5 axes yielded contradictory results for R_a values in some regions, but the overall surface roughness was better with the 5-axis method, because of the lower table rotation that resulted in a slower work feed rate.

Manufacture of silicon and germanium aspherics

The method for manufacturing glass aspherics is also applicable to Si and Ge. However, both Si and Ge are easier to machine as they are more homogenous in structure. Silicon finds 90% application in semiconductor electronic industries. It is also used for optical components in high resolution thermal imaging systems. Si and Ge continue to be the most widely used materials operating in the middle infra-red to far infra-red wavelength regions because of their unique properties. As in the case of glass, semi-ductile machining is clearly visible very much so in the case of monocrystalline Ge, as Figure 11 clearly shows. Though Si and Ge are very similar, their brittleness varies. They become increasingly ductile above 60% of their absolute melting temperatures, i.e. about 450°C for Ge and 750°C for Si (ref. 17). This may be a reason why more ductile regimes are seen with Ge.

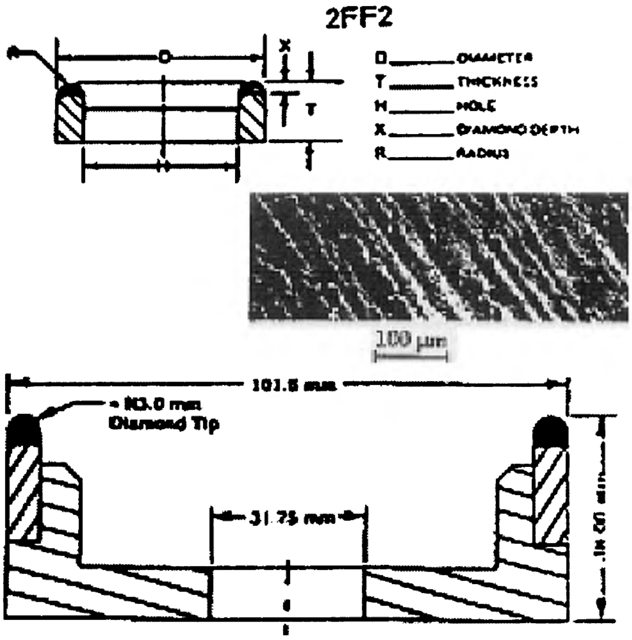

Figure 8. Cross-section and SEM picture of the metal-bonded grinding wheel based on 2FF2 design. Wheels typically used were M4D40/60 MIC-M100M-6MM. Grit sizes of 10, 20, 50, and 60 µm were used.

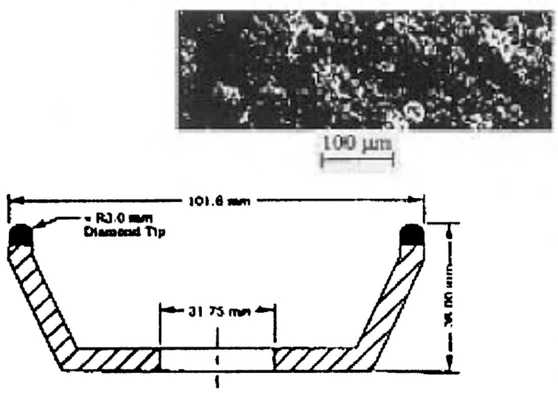

Figure 9. Cross section and SEM picture of the resinoid bonded grinding wheel. Wheels typically used were D40/60 MIC-R100B56-6MM. Grit sizes of 10, 20, 50 and 60 µm were used.

Manufacture of spherical silicon lenses

These products made in a local company were primarily for the US Army with production reaching a peak during the Gulf War. With the end of the Cold War, these lenses no longer have the military demand they once had, but production for the open market still continues on a modest scale. The manufacture involves three processes, viz. grinding, lapping (smoothing) and polishing. The spherical surfaces were generated using a Loh lens curve

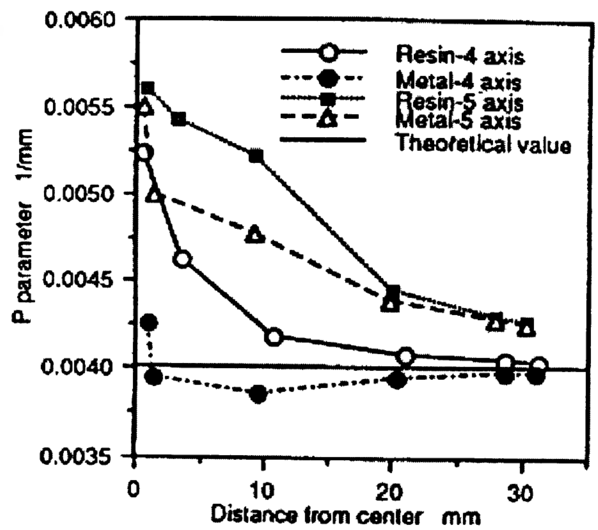

Figure 10. Parabolic parameters of the lenses ground by resinoid and metal-bonded grinding wheels with 4-axis and 5-axis methods.

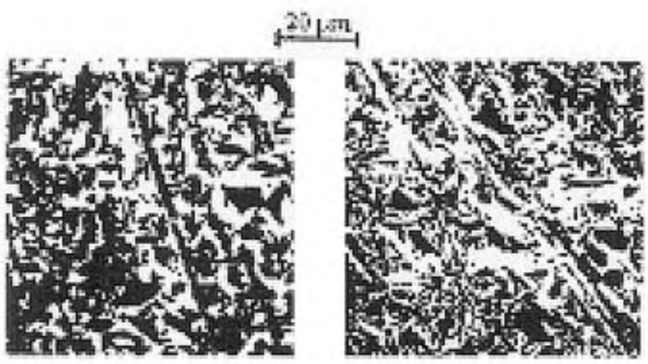

Figure 11. SEM pictures of ground mono-crystalline Si and Ge showing semi-ductile streaks which are more abundant in Ge.

generator and diamond cup grinding wheels. Then the workpieces were lapped using a Loh lapping machine and diamond pellets to smoothen the surfaces and plastic and/or pitch polishing was finally carried out to obtain good form and surface quality using a Loh polishing machine[3], as shown in Figure 12. Grinding shows no evidence of semi-ductile grinding zones, and this makes polishing more difficult even after lapping. Roughness results (Figure 13) indicate excellent surface finish[15].

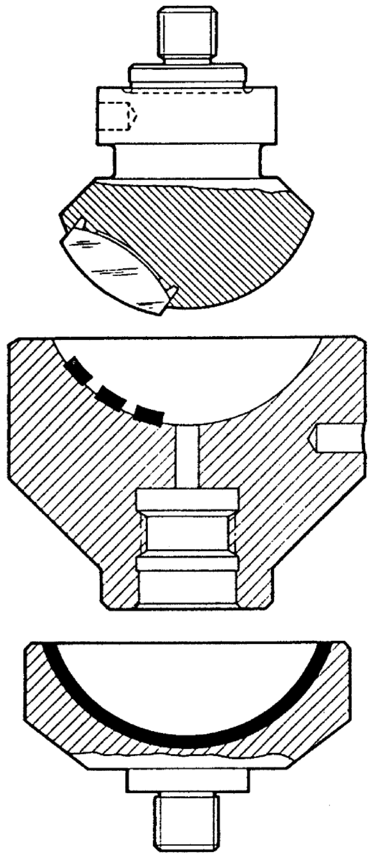

Figure 12. Recessed tool for holding lenses, diamond lapping tool and plastic and/or pitch polishing tool (ref. 3).

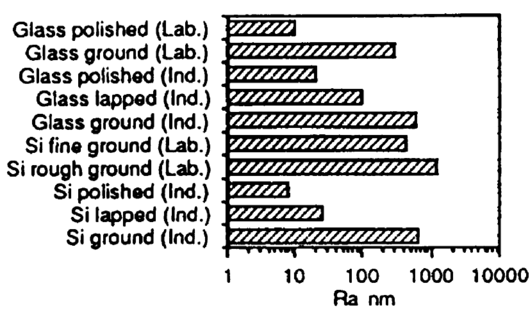

Figure 13. Roughness values of silicon spherical lenses of industrial origin are compared with other materials. The polished lens has the lowest R_a value, but at the expense of lapping and polishing time that resulted from obtaining grinding surfaces devoid of SEM-ductile features (ref. 15).

New revolutionary wheel

A new type of diamond grinding wheel has been developed that has no bond between the abrasives. The only bond needed is to anchor the diamonds onto the metallic substrate of the grinding wheel. Extremely fine diamond grits of about 3 μm size were developed. The wheel is particularly useful for ultra-precision grinding. This binderless diamond wheel is currently undergoing field trials on glass and silicon and is noteworthy for its ability to dramatically reduce polishing time during the secondary process. Large amounts of ductile streaks have been observed. It also has been able to grind IC Chip Packaging, a soft tough non-brittle material to reveal Cu traces and the dielectric for purposes of failure analysis. An invention disclosure has been submitted[18] and an application for a Malaysian Patent No. PI20030326 was filed on 30 January 2003 (ref. 19). This invention won a Silver Medal at the INPEX (Invention and New Products Exposition) show held from 15 to 18 May 2002 in Pittsburgh, PA, USA.

Conclusions

The manufacture of plastic lenses, especially the progressive addition lens, for ophthalmic purposes is gaining in popularity with decreasing costs brought about by low-cost manufacture of glass moulds. Ductile mode grinding has yet to gain worldwide attention in industries. Conventional grinding in many optical industries is highly successful. Semi-ductile grinding obtained by using conventional CNC machining centres and commercial grinding wheels is very promising and helps in reducing manufacturing costs. Semi-ductile grinding has been observed on glass, silicon and germanium. Of these three materials, germanium is the most prone to ductile machining and glass the least.

Generation of aspheric surfaces by the 4-axis method is faster and cheaper and provides better profile accuracy compared to the slower and more expensive 5-axis method.

The best fit concave radii were closer to the desired value for workpieces produced by metal-bonded wheels than that produced by resin bonded wheels. This is due to greater stiffness of the metal bond that permits profile accuracy during grinding. Resinoid-bonded wheels produce surfaces that are brighter due to decreased brittle fractures and increased ductile machining, than metal-bonded wheels.

1. Van Ligten, R. F. and Venkatesh, V. C., *Ann. CIRP*, 1985, **34**, 295–298.
2. Van Ligten, R. F. and Venkatesh, V. C., Invention – machine to make aspheric surfaces, National University of Singapore, Patent disclosure, 1986.
3. Horne, D. F., Optical Production Technology, Adam Hilger, Bristol, 2nd edn, 1983.

4. Davis, D. W., Walker, M., Takashi, M. and Masaki, T., *Sadhana*, 2003 (in press).
5. Taniguchi, N., *Precis. Eng.*, 1994, **16**, 5–24.
6. Miyashita, M., 'Brittle/ductile machining', Fifth International Seminar on Precision Engineering Monterey, CA, USA, 1989.
7. Venkatesh, V. C., Chee, W. K., Pey, K. L., Tan, K. H. and Trigg, A., 'Surface integrity of polished infra-red optics and glass', Proceedings of 11 American Society of Precision Engineering Conference, Monterey, CA, USA, 1996, Vol. 14, pp. 490–495.
8. Schinker, M. G., *J. Precis. Eng.*, 1991, **13**, 208–218.
9. Bifano, T. G., DePiero, D. K. and Gollini, D., *J. Precis. Eng.*, 1983, **15**, 238–247.
10. Tan, C. P., CNC rough grinding of aspheric surfaces, B Eng (Mech.) Thesis, National University of Singapore, 1984.
11. Ang, K. W., Economic analysis of aspheric surface grinding using 4 and 5 axes generation on vertical machining CNC Centres, M S Thesis, Tennessee Technological University, 1989.
12. Tan, C. P., Aspheric surface grinding and polishing of thermal imaging materials, M S Thesis, Tennessee Technological University, 1990.
13. Russell, R. G., Comparison of metal and resinoid bonded grinding wheels with various grit sizes in the aspheric surface generation of silicon lenses, M S Thesis, Tennessee Technological University, 1993.
14. Kapoor, A., A study on mechanisms of aspheric grinding of silicon, M S thesis, Tennessee Technological University, 1993.
15. Zhong, Z. and Venkatesh, V. C., *Ann. CIRP*, 1994, **43**, 323–326.
16. Venkatesh, V. C. and Silva, D., 'On the wear of diamond tools in numerical control contour generation', Proceedings of International Conference on Optimum resources utilisation through tribo-tetro-technology, New Delhi, India, 1981, pp. J2. 1–8.
17. Blake, P. N., Ductile-regime turning of Ge and Si, Ph D Thesis, North Carolina State University, Raleigh, 1988.
18. Venkatesh, V. C. and Izman Sudin, 'Novel diamond wheel for fine finishing of I. C. chip packaging material for failure analysis and for machining small areas in brittle materials like silicon and glass', Invention disclosure made on 18 March 2002, University Technology Malaysia, Johor Bahru, Malaysia, 2002.
19. Venkatesh, V. C. and Izman Sudin, Application for Malaysian Patent for above invention filed on 30 January 2003. No. PI 20030326.

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First evidence for anomalous thick crust beneath mid-Archean western Dharwar craton

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We report an anomalous present day crustal thickness of 43–52 km beneath the 3.4–3.0 Ga mid-Archean segment of the western Dharwar craton (WDC) undisturbed by Proterozoic events. In contrast, adjoining late-Archean (2.7–2.5 Ga) eastern Dharwar craton (EDC) has a 33–40 km crustal thickness similar to the Archean global average. Considering that mineral assemblages in the central part of the WDC crust (amphibolite grade metamorphics) equilibrated at a depth of 15–20 km, we argue that the western Dharwar crust 3.0 Ga ago must have been at least 60–80 km thick. Both segments of Dharwar craton crust exhibit Poisson's ratio of 0.24–0.28 suggesting felsic to intermediate average crustal composition. The thickest crust beneath WDC has also underlying high-velocity thicker lithosphere compared to EDC, inferred from faster arrivals of teleseismic P and S wave. The contact between WDC and EDC is marked as gradational thinning of crust (42–36 km) from Chitradurga thrust to the western part of Closepet granite. In WDC, the crustal thickness increases in step fashion towards the oldest crustal block. These details suggest terrain accretion in Dharwar craton during 3.4 to 2.5 Ga through subduction related process.

THE origin and growth of the Archean crust is a subject of intense investigation. The geological, geochemical and geophysical observations suggest a fundamental difference between early- and mid-Archean crust with those evolved during and subsequent to the late Archean[1]. Our understanding about the nature of the early crust and it's possible variation through geological time remains incomplete due to insufficient knowledge about the thickness and composition of the undeformed early- and mid-Archean crust. Global review of seismological data[2,3] suggests that the Precambrian shields have an average

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