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Ductile or Partial Ductile Mode Machining of Brittle Materials

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This paper reports ductile or partial ductile mode machining of silicon, glass and some advanced ceramics. Results are presented using scanning electron micrographs of the machined surfaces. Grinding and lapping operations using inexpensive machine tools could produce ductile streaks on surfaces of these brittle materials under good conditions. Manufacture of spherical glass lenses by the fracture mode or partial ductile mode grinding followed by partial ductile mode lapping and ductile mode polishing is fast and economical. Using partial ductile mode grinding and ductile mode polishing has also been very successful for manufacturing aspherical glass lenses. Reduced polishing time and improved surface quality are due to the presence of ductile streaks. Ground silicon, ZrO_2 and Al_2O_3 also showed ductile streaks. Toroidal SiC surfaces ground with flat-face cup wheels indicated 100% ductile machining, and did not require polishing.

Keywords: Brittle materials; Ductile streaks; Mirrors; Partial-ductile mode machining; SEM analysis; Surface roughness

1. Introduction

Single-point diamond turning is one of the popular methods for machining precision/ultraprecision optical lenses and mirrors. However, this technique cannot be used for generating nonsymmetrical surfaces like toroids with large radii of curvature and progressive lenses made of brittle materials. Grinding, lapping and polishing therefore continue to be important processes for shaping brittle materials. In fact, current industrial manufacture of lenses and mirrors usually involves these three operations.

Advanced ceramics such as silicon carbide, aluminum oxide, and zirconium oxide are becoming significantly important materials [1, 2]. Machining of ceramics is often needed to obtain the dimensions and accuracy required for applications. Due to their high hardness, grinding using a diamond wheel is often the finishing process used [3].

Researchers and manufacturers have made a lot of effort to machine these important brittle materials with low surface roughness and subsurface damage [4–6]. Conventional grinding of brittle materials normally produces 100% fractured surfaces requiring lapping and polishing. However, the concept of ductile mode machining has led to many innovative applications for machining brittle materials, such as glass, Si, Ge and SiC [7–11]. Research on grinding Si and Ge has revealed that ductile chips can be obtained by properly controlling the depth of cut [12]. A model for the critical depth associated with ductile mode machining has been proposed [13]. Flawless machining, free of brittle fracture, was achieved by having a depth of cut not greater than a critical depth and having flattened grains slightly protruding from the surface of the grinding wheel [14]. When ductile mode machining of brittle materials is achieved, nanometre order surface roughness is obtained and subsurface damage approaches zero.

Ductile and brittle modes of deformation can happen in the same brittle material and the transition between them can be controlled by changing machining conditions. The deformation transition regimes can be divided into four types. The regime in which the deformation takes place in the form of simple plastic flow is the favoured regime for ductile mode machining [15]. The effects of the crystallographic directions and process conditions on ductile mode machining of Si and Ge were also investigated [16–19]. The critical depths of cut changed depending on the machining directions and coolant fluids used. For the ductile mode grinding of hard and brittle materials, the critical machining depth ranges from 50 nm to 1 μm [20].

To perform 100% ductile mode machining of brittle materials, machine tools with high-accuracy servomechanisms (resolution 1.25–10 nm), high loop stiffness, and full flood coolant and a depth of cut less than 1 μm must be used [21]. Examples of such machine tools are ultraprecision machines for ultraprecision grinding or single crystal diamond turning. Because these ultraprecision machine tools and cutting tools that are manufactured to submicron tolerances are expensive, ductile mode machining has not yet gained worldwide acceptance, although its application has been known, by industry.

Therefore, research on ductile mode fine grinding has been carried out on less expensive and conventional machine tools.

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Grinding wheels with rigid bonds and small-size diamond grains are used for the fine grinding of brittle materials [22–25]. These techniques result in the ductile mode fine grinding of brittle materials which produce a mirror surface finish (nanometre order surface roughness) and which do not require further finishing operations such as polishing [26, 27]. In our laboratory studies, mirrors and lenses have been manufactured only with a grinding process, using the 100% ductile mode material removal process in grinding.

However, some research work reported in this paper 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. Miyashita has made a very fine analysis of the transition from conventional grinding to ductile mode grinding. Miyashita's chart [21] shows the brittle-to-ductile transition, indicated as microcrack grinding. Microcrack grinding can be described as partial ductile grinding that takes into account the ductile aspect. Partial ductile grinding and lapping appear to be more attractive alternatives to the optical industry, because the grinding wheels, lapping tools and the machines are reasonably priced. Partial ductile grinding and lapping obtained by using conventional machines, CNC machining centres and commercial tools, works well, especially for the ophthalmic industry [10].

This paper reports on the ductile or partial ductile mode of machining of silicon, glass and some advanced ceramics. Ductile streaks can be obtained by grinding and lapping. The machines used for the experiments reported in this paper are not expensive ultraprecision machines. In some experiments reported here, spherical glass surfaces were machined by partial ductile mode grinding and lapping in the optical industry using conventional machines and grinding and lapping tools. This significantly shortened the polishing time. Partial ductile aspherical glass surfaces could also be obtained in the optical industry on a CNC machining centre, and these surfaces could be directly polished, reducing the polishing time and eliminating the lapping process. A significant reduction in polishing time as a result of increasing the number of ductile streaks is reported. Ductile grinding of silicon, SiC, ZrO_2 and Al_2O_3 was also achieved. The issues discussed here are surface roughness, microfractures and ductile streaks on the surfaces of machined brittle materials.

2. Experiments

2.1 Grinding of Ceramics

ZrO_2 and Al_2O_3 were ground on a surface grinding machine with diamond grinding wheels. Wheel depths of cut were 0.1, 0.5, 1 and 8 μm, feedrate 24 m min^{-1}, without crossfeeding. The grinding speed was 40 m s^{-1} (2400 m min^{-1}, 2150 r.p.m.). The grinding wheels were trued by using a braked truing device after mounting.

2.2 Machining of Spherical and Aspherical Glass Lenses

The spherical glass surfaces were generated using conventional curve generators and diamond grinding wheels with large grains. The surfaces were then lapped by using diamond pellets to smooth the fractured surfaces, followed by polishing. Machining aspherical glass surfaces was carried out on a conventional aspherical generator and a CNC aspheric generator, both with metal-bonded diamond wheels. This was followed by polishing on conventional spherical polishing machines.

2.3 Grinding, Lapping and Polishing of Si Lenses

Some spherical Si lenses analysed for comparison in this paper were from industrial sources. The spherical surfaces were ground using diamond cup grinding wheels. Then the workpieces were lapped using diamond pellets to smooth the surfaces. Finally, polishing was carried out to obtain good form and surface quality. The time consumed in grinding and lapping processes was short, but the polishing time was relatively long.

2.4 Grinding of Aspherical SiC and Si Mirrors

SiC beam deflectors used in synchrotron radiation facilities are toroidal, elliptic and circular-cylinder surfaces with large radii of curvature of several or even more than 100 m [28,29]. The requirements for surface roughness and shape accuracy of the mirrors are extremely high. Traditionally, in the finishing process, loose abrasives were usually used and manual operations were carried out by trial and error while repeatedly performing shape inspections. It had long been a manufacturer's dream to grind automatically large-radii toroidal surfaces with high shape accuracy and very low surface roughness. To meet this demand, a precise positioning system was developed [30, 31]. Automatic grinding of toroidal surfaces was conducted using this position system [26].

An inexpensive machining centre (controlled axes: three axes; least input increment: 1 μm) was used as a grinding machine. A microdisplacement table [30, 31] was attached to the machining centre. The materials of the workpieces were mainly solid SiC and SiC CVD coated on graphite. Some workpieces were also of silicon. Silicon carbide is said to be one of the best materials for the mirrors used in synchrotron radiation facilities. Silicon is widely used in semiconductor and electronics industries, as well as optical components in high-resolution thermal-imaging systems.

Cast-iron fibre-bonded diamond wheels (peripheral and flat-faced cup wheels), of mesh number #8000, were used as finish grinding wheels. For rough grinding, meshes of #325 and #1200 were used. A SiC wheel mounted on a brake-controlled truing device was used for truing and dressing of the grinding wheels. The truing and dressing conditions were peripheral velocity of grinding wheel = 140 m min^{-1}, crossfeed velocity = 100 m min^{-1}, and depth increment after each traverse = 1 μm. The finish grinding conditions were peripheral velocity of grinding wheel = 1200 m min^{-1}, table speed = 100 mm min^{-1}, and depth of cut = 1 μm.

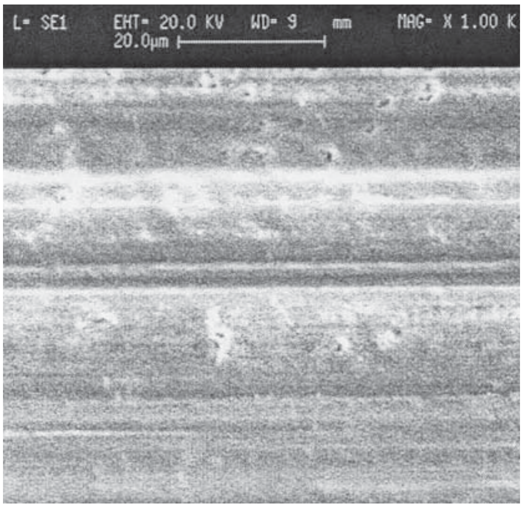

Fig. 1. Ductile streaks on ground ZrO_2.

2.5 Grinding of Flat Si Surfaces

A conventional surface grinding machine with a spindle speed of 1450 r.p.m. was used. A dressing stick was manually pushed onto the wheel face. Such an operation did not provide a constant infeed and force. Furthermore, manual application of a dressing stick results in a poor wheel profile. Therefore, a simple dressing device and an improved coolant system were developed [32]. Grinding experiments were carried out using a resin-bonded diamond wheel (grit size 1500) with crossfeed 0.5 mm, table speed 5 m min^{-1}, and infeed of 0.1 μm. Dressing sticks used were WA400G Al_2O_3 sticks.

3. Results and Discussion

The surfaces of the machined brittle materials were assessed by the measurement of the surface roughness using a profilometer and observation using a scanning electron microscope (SEM).

The surface of ZrO_2 test piece ground with a 125-grit diamond wheel at grinding speed 2400 m min^{-1}, feed rate 24 m min^{-1}, depth of grinding 0.5 μm and without crossfeed showed ductile streaks as shown in Fig. 1. Plastic deformation was the major mechanism of the material removal at high wheel speeds. The removal mechanism for ZrO_2 particularly at a high wheel speed was similar to that for metals. The surface texture was improved due to folding of the asperities. Ground Al_2O_3 surfaces at a low wheel speed developed plastic bulges but showed more brittle fractures, as shown in Fig. 2(*a*). At a high wheel speed, the grooves were smooth, and as shown in Fig. 2(*b*) there was a large amount of plastic flow of the material with microploughing due to the thermal effect, which is similar to that for ground ductile metals [33].

In the optical industry, diamond cup wheels are used to generate spherical surfaces without frequent dressing. The grit size used is relatively large. The surface roughness after grinding is poor, though the material removal rate is high. Therefore, lapping and polishing operations are essential and the polishing time is relatively long. The glass samples machined by conventional grinding (Fig. 3(*a*)) show 100% fractured surfaces. Lapping of spherical glass lenses produces some partial ductile streaks on the lapped surfaces. However, under optimal grinding and lapping conditions, more partial ductile mode surfaces could be obtained (Figs 4 and 3(*b*)). This resulted in significantly shortened polishing time for producing an acceptable surface finish.

When an old machine was used for grinding aspherical glass surfaces, no ductile streaks were formed even at fine feeds. A polishing time of 8 minutes was necessary. Ductile grinding streaks on aspherical glass surfaces were obtained by using the CNC machine and good grinding conditions. An enlargement of a ductile streak (Fig. 5) shows material displacement similar to that which Kitajima et al. [34] have shown with ceramics. Because of these ductile grinding streaks, the polishing time of 8 minutes was reduced by 50% to 4 minutes.

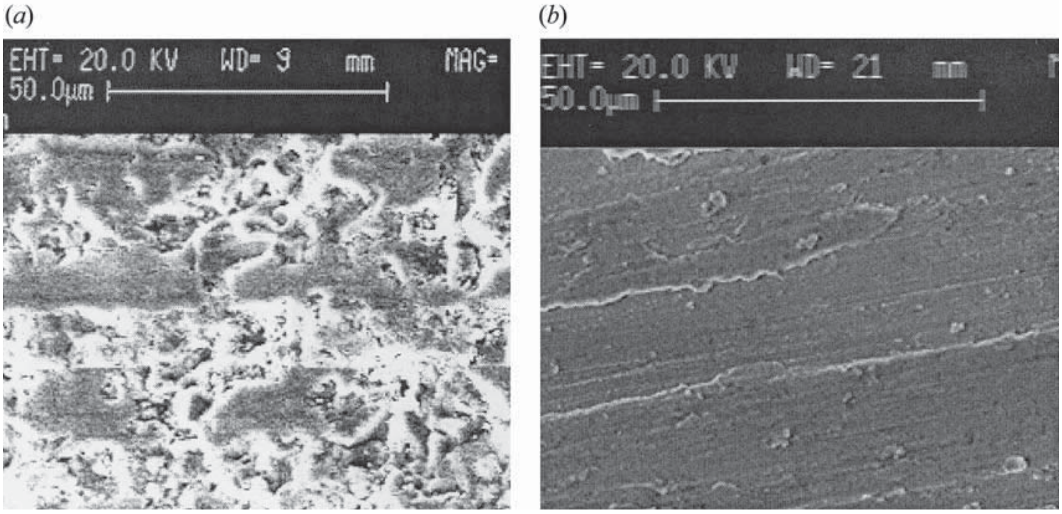

Fig. 2. Ductile streaks on ground Al_2O_3 at (*a*) a low wheel speed and (*b*) a high wheel speed [33].

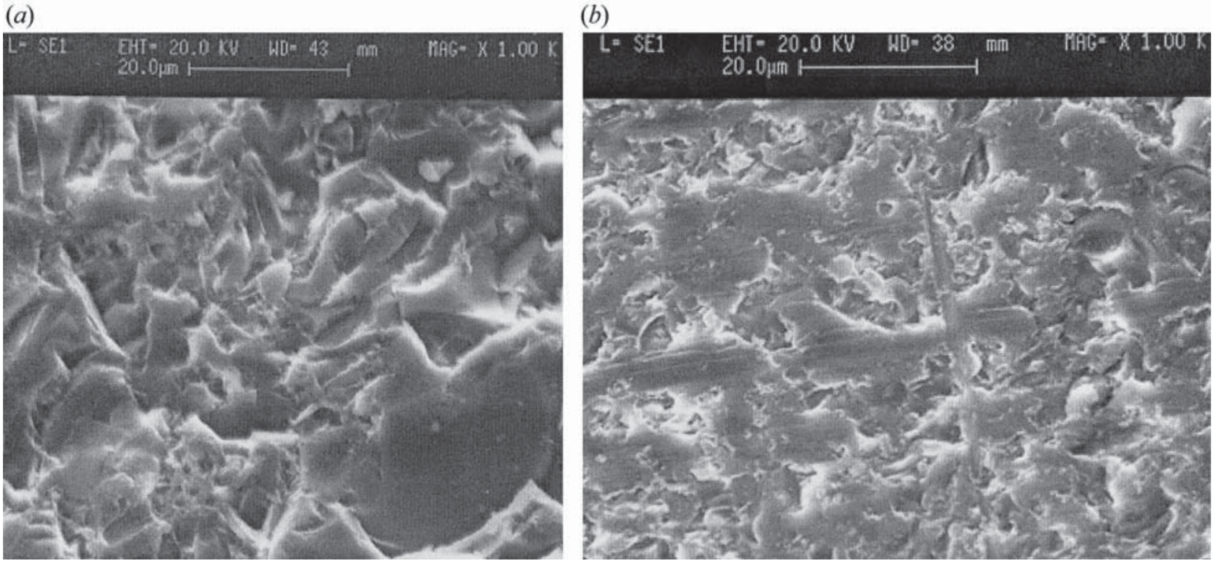

Fig. 3. SEM pictures of spherical glass surfaces machined (*a*) by conventional grinding showing a 100% fractured surface, and (*b*) by optimal lapping showing a partial ductile mode machined surface.

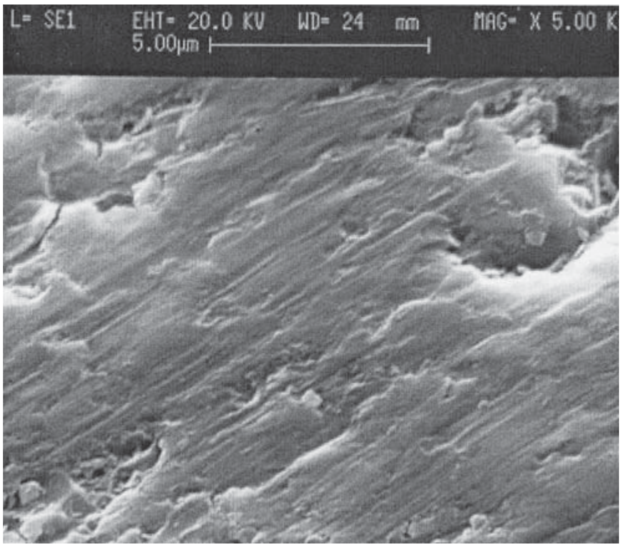

Fig. 4. SEM picture of ground spherical glass surface, showing ductile streaks.

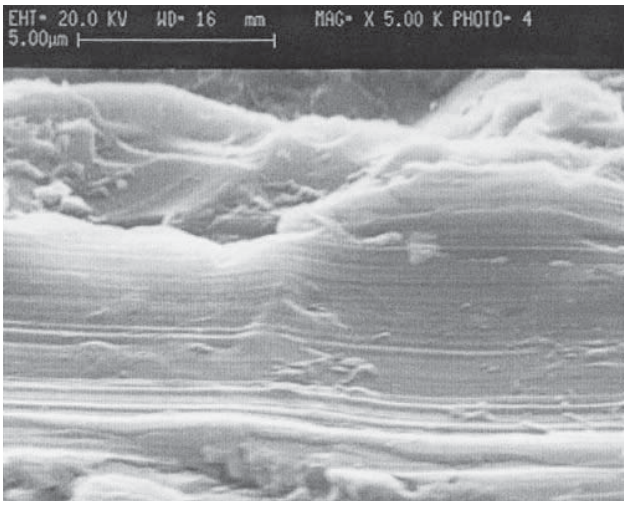

Fig. 5. SEM picture of ground aspherical glass surface, clearly showing material displacement.

The curves of surface roughness versus polishing time are shown in Fig. 6. The knee points in the polishing curves have been reported earlier by Parks and Evans [35]. Samples 1 and 2 had a similar surface finish after grinding and were polished with fresh and old polishing powder, respectively. Because sample 3 had the most ductile streaks after grinding, its curve is the lowest one in Fig. 6, although old polishing powder was used.

These results show that each preceding process is very important for the successive processes. To reduce the total manufacturing time, it is preferable to obtain better ground or/and lapped surfaces with as many ductile streaks as possible.

Figure 7 shows SEM pictures of silicon surfaces obtained by grinding and lapping operations in the optical industry. The microfractures on ground surfaces and the more ductile mode of lapped silicon can be seen clearly.

Figure 8 shows SEM pictures of the ground flat surfaces of silicon. As shown by Fig. 8(*b*), ductile mode grinding of silicon was achieved using a diamond grinding wheel with a grit mesh size of 1500 on a conventional grinding machine. By using the simple device to dress the diamond wheel, better surface finish could be achieved than when a conventional manual dressing method was used (Fig. 8(*a*)). A decreased nozzle distance from the wheel improved the cooling perform-

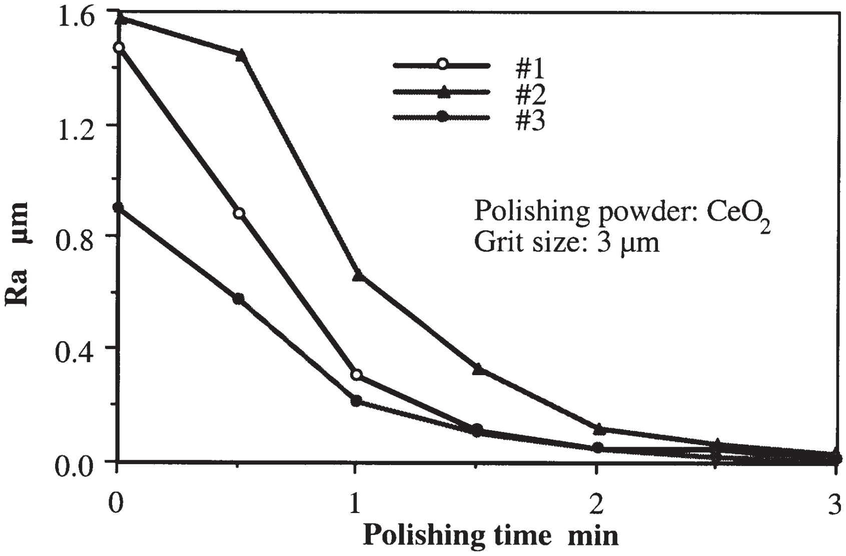

Fig. 6. Roughness (Ra) of polished aspheric glass surface versus polishing time.

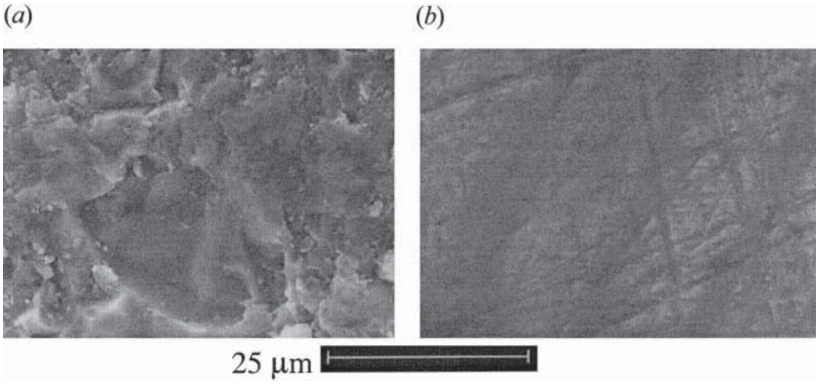

Fig. 7. SEM pictures of spherical silicon surfaces obtained by (*a*) grinding and (*b*) lapping.

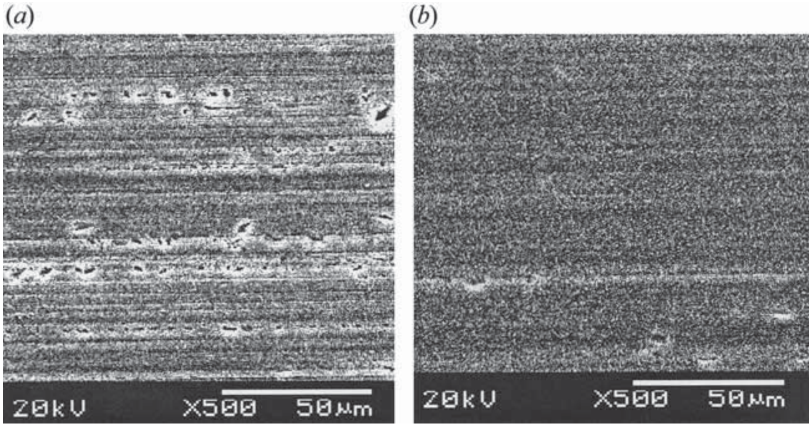

Fig. 8. (*a*) SEM picture of silicon ground after manual dressing with a dressing stick and using the original coolant system. (*b*) SEM picture of silicon ground after dressing with the new dressing device and using the improved coolant system [32].

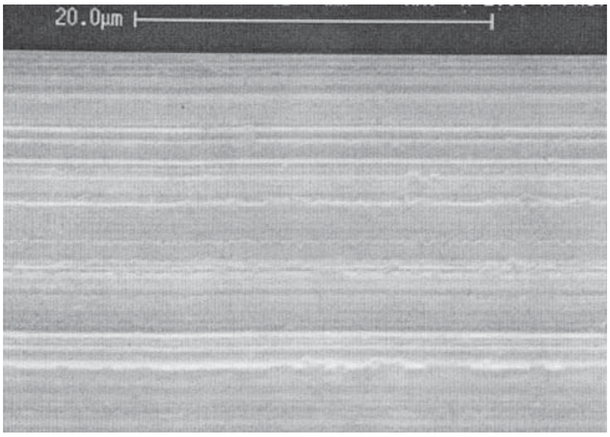

Fig. 9. SEM micrograph of a toroidal Si surface obtained by ductile mode grinding.

ance at the grinding zone when using the flexible nozzles of the improved coolant system. A flooding supply of coolant could be deployed at the grinding zone which provided a better cooling performance, lubrication and better wheel cleaning [32].

Figure 9 shows ductile mode grinding of a toroidal Si surface obtained in the laboratory. Figure 10 shows SEM pictures of toroidal SiC surfaces obtained by grinding only. SiC ground using a peripheral grinding wheel has a good surface as shown in Fig. 9(*a*), indicating an almost 100% ductile mode machining. Toroidal SiC surfaces ground with flat-face cup wheels indicate 100% ductile mode machining as shown in Fig. 9(*b*), and do not require polishing. The surface roughness of ground SiC mirrors is very low. Mirror surfaces can be obtained by grinding operations without the need for polishing. Roughness improves with a decreasing grit size of diamond grinding wheels and increasing diamond concentration, and in these conditions the dressing methods and conditions become more important.

4. Summary

Grinding using inexpensive machine tools could produce ductile streaks on glass and Si surfaces. Under optimal grinding and lapping conditions, more partial ductile mode surfaces could be obtained. This results in significantly shortened polishing time to obtain an acceptable surface finish. To reduce the total manufacturing time, it is preferable to obtain better ground/lapped surfaces with as many ductile streaks as possible and to reduce the polishing time. Ductile mode grinding of silicon was achieved using a simple dressing device and an improved coolant system. Ground ZrO_2 and Al_2O_3 also showed ductile streaks. Toroidal SiC surfaces ground with flat-face cup wheels indicated 100% ductile machining, and did not require polishing. The machines used for the experiments reported in this paper are not expensive ultraprecision machines.

Manufacture of spherical glass lenses by fracture mode or partial ductile mode grinding followed by partial ductile mode

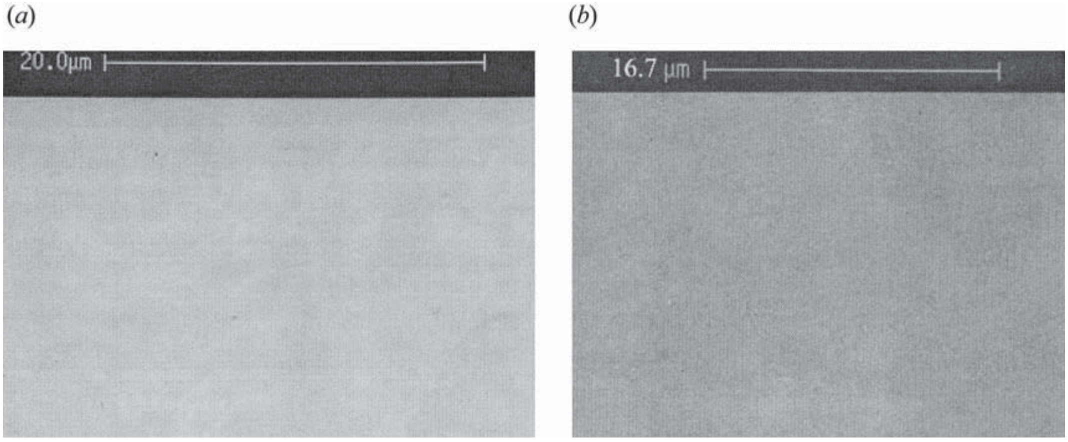

Fig. 10. SEM pictures micrograph of a SiC surface obtained by ductile mode grinding with (*a*) a peripheral wheel and (*b*) a flat-face cup wheel.

lapping and ductile mode polishing is fast and economical. Reduced polishing time and improved surface quality are due to the presence of ductile streaks. Using partial ductile mode grinding and ductile mode polishing has been very successful for manufacturing aspherical glass lenses. Again, an increase in ductile streaks helps to reduce polishing time and improve surface quality. Partial ductile grinding and lapping obtained by using conventional machines and commercial tools works well for the ophthalmic industry, and results in reduced manufacturing costs.

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