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Surface finish of precision machined advanced materials

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Abstract

This paper studies the surface finish and integrity of glass, silicon, some advanced ceramics and aluminum-based metal matrix composites (MMCs) reinforced with ceramic particles, precision machined by various machining processes. The studies revealed that grinding/lapping operations using inexpensive machine tools can produce ductile streaks on glass and silicon surfaces under good grinding/lapping conditions. This resulted in significantly shortened polishing time to secure an acceptable surface finish. If there are several processes to manufacture a lens, each preceding process is very important for the successive processes. In order to reduce the total manufacturing time, it is preferable to obtain better ground/lapped surfaces with as many ductile streaks as possible in order to reduce the polishing time. Toroidal SiC surfaces ground with flat-face cup wheels indicated 100% ductile machining, and did not require polishing. Ground ZrO_2 showed a numerous ductile streaks. Plastic deformation was the major mechanism of material removal at high wheel speeds. Grinding of aluminum-based MMCs reinforced with Al_2O_3 or SiC particles using a 3000 grit diamond wheel at depths of grinding of 1 and 0.5 μm produced many ductile streaks on the Al_2O_3 and SiC particles, respectively. There was almost no sub-surface damage. The machines used for the experiments reported in this paper are not expensive ultra-precision machines.

Keywords: Surface finish and integrity; Advanced materials; Ductile streaks

1. Introduction

Glass, silicon, advanced ceramics such as silicon carbide, aluminum oxide, and zirconium oxide, and aluminum-based metal matrix composites (MMCs) reinforced with ceramic particles are becoming significantly important materials. Many of them belong to the group of difficult-to-machine materials. All of them are either brittle materials or have brittle and hard particles. There will be a greater demand to develop techniques for generating surfaces of such advanced materials with high precision in surface finish, due to the increasing requirements for better surface quality, and higher precision and productivity in the future.

Researchers have made much effort to manufacture highly precise devices with good surface finish, and low sub-surface damage, at reduced costs [1–8]. The concept of ductile mode machining has led to many innovative applications for manufacturing lenses and mirrors [6–11]. Konig and Sinhoff [12] have shown that flawless machining, free of brittle fracture, is possible by having a critical depth of cut and flattened grains slightly protruding from the surface of the grinding wheel.

Grinding, lapping and polishing are important processes for shaping brittle materials. The industrial manufacture of lenses usually involves these three operations. While these three operations have been successful for machining spherical lenses, aspherical lenses have been manufactured in the absence of the lapping process, because of the considerable amount of ductile mode of material removal in grinding. In our laboratory studies, mirrors and lenses have been manufactured only with a grinding process, because of 100% ductile mode material removal in grinding.

Grinding is one of the final processes for finishing aluminum-based MMCs reinforced with ceramic particles to obtain good surface finish, achieve high dimensional accuracy, as well as remove damaged layers. However, studies to obtain damage-free surfaces are still required for the application of the materials.

This paper studies the surface finish and integrity of glass, silicon, some advanced ceramics and aluminum-based MMCs reinforced with ceramic particles, precision machined by various machining processes. Ductile streaks can be obtained by grinding and lapping. The machines used for the experiments reported in this paper are not expensive ultra-precision machines. A significant reduction in polishing time as a result of increasing the number of ductile streaks is reported. The parameters that helped to identify

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and solve problems in manufacturing were surface roughness, micro-fractures and ductile streaks on the surfaces of machined brittle solids or particles.

2. Experiments

2.1. Grinding, lapping and polishing of spherical glass lenses

The spherical surfaces were generated using diamond cup grinding wheels. Then the workpieces were lapped using diamond pellets to smoothen the surfaces. Finally, plastic polishing was carried out to obtain good surface quality.

2.2. Grinding and polishing of aspherical glass lenses

Grinding of aspherical glass lenses was undertaken with metal-bonded diamond wheels (grit size: 20 μm) in two ways: (1) using an old, conventional, aspherical surface generator and (2) its newer precision version. The old, conventional machine used in-feeds of 0.1, 0.2 and 0.3 mm and a depth of cut of 0.05 mm, whilst the new precision machine used in-feeds of 0.05 and 0.1 mm but with a stock removal of 0.2 mm. Grinding was followed by conventional polishing without the intervention of a lapping process.

2.3. Grinding of SiC and Si mirrors

A vertical machining center (controlled axes: three axes; least input increment: 1 μm) was used as a grinding machine. Cast-iron fiber-bonded diamond wheels (straight type and flat-faced cup type), 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 the truing and dressing of the grinding wheels. The truing and dressing conditions were peripheral velocity of grinding wheel = 140 m/min, cross-feed velocity = 100 mm/min, and depth increment after each traverse = 1 μm. Barrel-shaped wheels were profiled with a diamond dresser after truing of them with the brake-controlled truing device. The finish grinding conditions were peripheral velocity of grinding wheel = 1200 m/min, table speed = 100 mm/min, and depth of cut = 1 μm. When traverse grinding operation was performed for machining toroidal mirrors, the cross-feed was 0.3 mm.

2.4. Grinding, lapping and polishing of Si lenses

Some spherical silicon lenses analyzed 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 smoothen the surfaces. Finally, polishing was carried out to obtain good form and surface quality. The time consumed in grinding and lapping processes is short, but the polishing time is relatively long.

2.5. Grinding of ceramics

Al_2O_3, ZrO_2, and AT (alumina and titanium mixture, a hybrid ceramic) were ground on a surface grinding machine. A resin-bonded diamond wheel was used to grind the ceramic specimens. The wheel depths of cut were 0.1, 0.5, 1 and 8 μm, the feed rate were 24 m/min, without cross-feeding, the grinding speed was 40 m/s (2150 rpm). The diamond grinding wheel was trued using a braked truing device after mounting.

2.6. Grinding of MMCs

Experiments of grinding MMCs were conducted on a surface grinding machine. A resin-bonded diamond grinding wheel was used. The grit size was 3000 (5 μm average grain size). The depths of cut were 0.1, 0.2, 0.5 and 1 μm, the feed rate was 20.8 m/min and the cross-feed was 1 mm. The grinding speed used was 1100 m/min (1000 rpm). The diamond grinding wheel was trued using a braked truing device immediately after mounting. Dressing was carried out at the beginning of the grinding for each specimen by using a WA dressing stick of 320 grit for fine grinding.

2.7. Assessment of machined surfaces

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

3. Results and discussion

Fig. 1 shows SEM micrographs of silicon surfaces obtained by grinding, lapping and polishing operations in the optical industry. The grinding and lapping streaks/grooves, micro-fractures on ground surfaces and the more ductile mode of lapped silicon, can be seen clearly. Polished silicon has a very good surface indicating 100% ductile machining, but a long processing time of up to 6 h is needed. Sometimes even after 6 h polishing, defective areas can still be found. Fig. 2 shows ductile-regime grinding on a toroidal silicon surface obtained from the laboratory work.

These pictures show that each preceding process is very important for the successive processes. In order to reduce the total manufacturing time, it is preferable to obtain better ground surfaces, even if this takes a little longer grinding time, to reduce the polishing time.

Fig. 3 shows SEM micrographs of toroidal SiC surfaces obtained by grinding. It can be seen clearly from (a) that plunge grinding produces ductile streaks on the SiC surface. SiC obtained by traverse grinding has a good surface as shown in (b), indicating almost 100% ductile mode machining, although the time expended in the process becomes longer than that for the plunge grinding operation. Toroidal

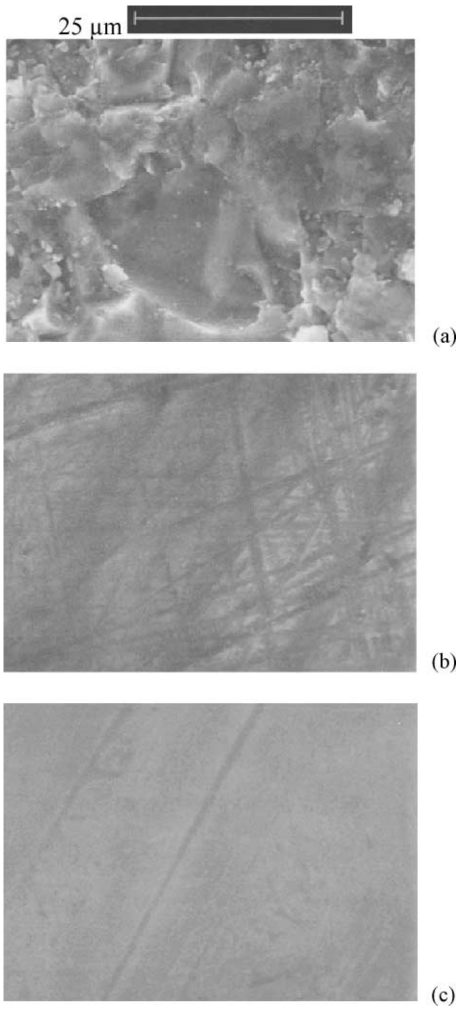


Fig. 1. SEM micrographs of spherical silicon surfaces obtained by: (a) grinding; (b) lapping; (c) polishing operations.

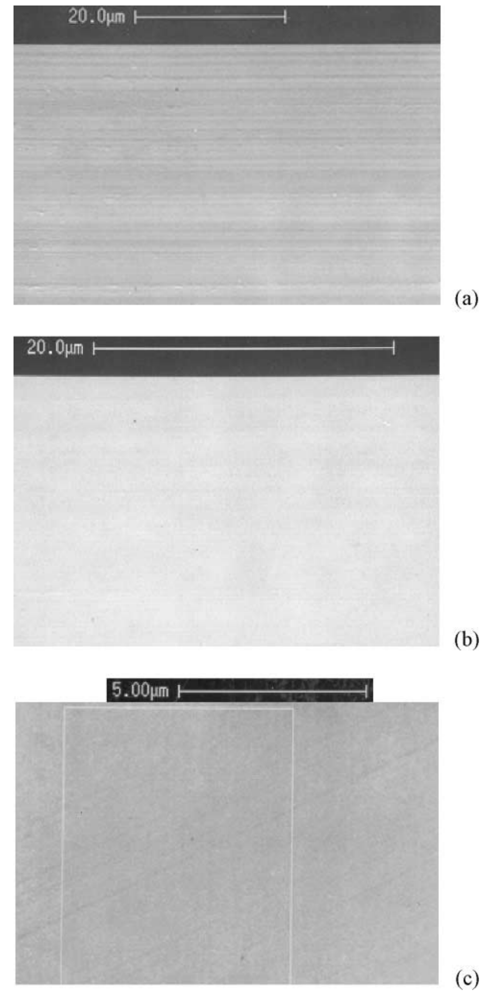


Fig. 3. SEM micrographs of ductile mode SiC surfaces obtained by: (a) plunge grinding; (b) traverse grinding; (c) grinding using cup wheel.

SiC surfaces ground with flat-face cup wheels indicate 100% ductile machining, shown in (c) and do not require polishing.

Fig. 4 shows the surface roughness values of ground SiC and Si from laboratory work, and ground, lapped and polished Si surfaces from industry. The surface-roughness values of ground silicon carbide and silicon mirrors are very low and they are independent of the direction of measurement. Mirror surfaces can be obtained by grinding operations without the need for polishing. The roughness improves with decreasing grit size of the diamond grinding wheels and increasing diamond concentration, while the dressing methods and conditions become more important.

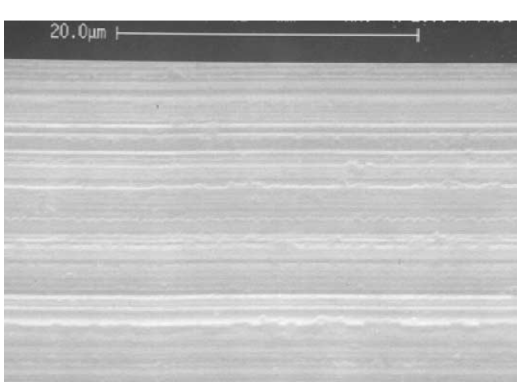


Fig. 2. SEM micrograph of a toroidal Si surface obtained by grinding.

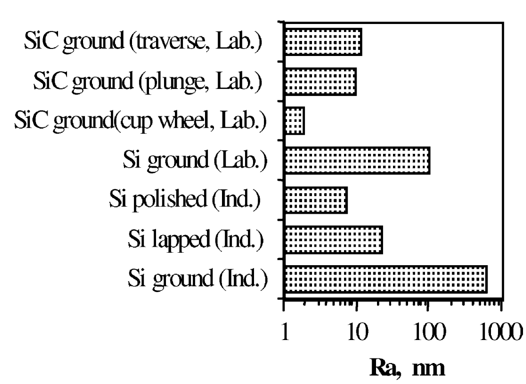


Fig. 4. R_a of ground, lapped and polished Si and SiC surfaces.

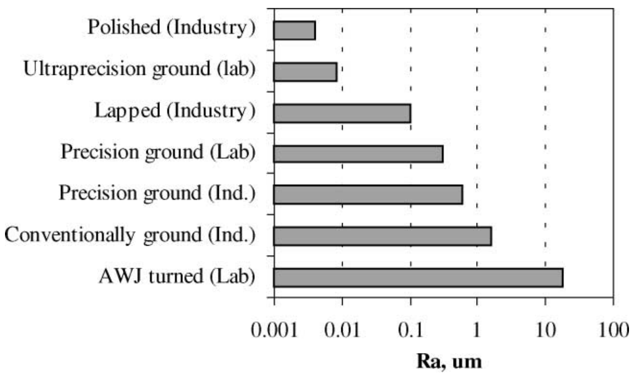


Fig. 5. R_a of glass surfaces obtained from various processes.

Fig. 5 compares the surface roughness of glass surfaces machined by abrasive waterjet (AWJ) turning [13], conventional grinding, precision grinding, ultra-precision grinding, lapping and polishing. The glass samples machined by AWJ turning (Fig. 6(a)) and conventional grinding (Fig. 6(b)) are 100% fractured surfaces. Lapped glass (Fig. 6(c)) reveals some ductile streaks and polished glass shows a perfect mirror surface (Fig. 6(d)). Under optimal grinding and lapping conditions, more partial-ductile mode surfaces could be obtained. This resulted in significantly shortened polishing time to secure an acceptable surface finish.

When the old, conventional machine was used for grinding aspherical glass surfaces, no ductile streaks were formed even at fine feeds. A polishing time of 8 min was necessary. Also, the profile was often not satisfactory when tested with a Moiré deflectometer.

Ductile grinding streaks on aspherical glass surfaces were obtained by using a new precision machine and good grinding conditions. Fig. 7(a) shows ductile grinding streaks. An enlargement of the ductile streak as shown in Fig. 7(b) is a clear indication of material displacement. With these

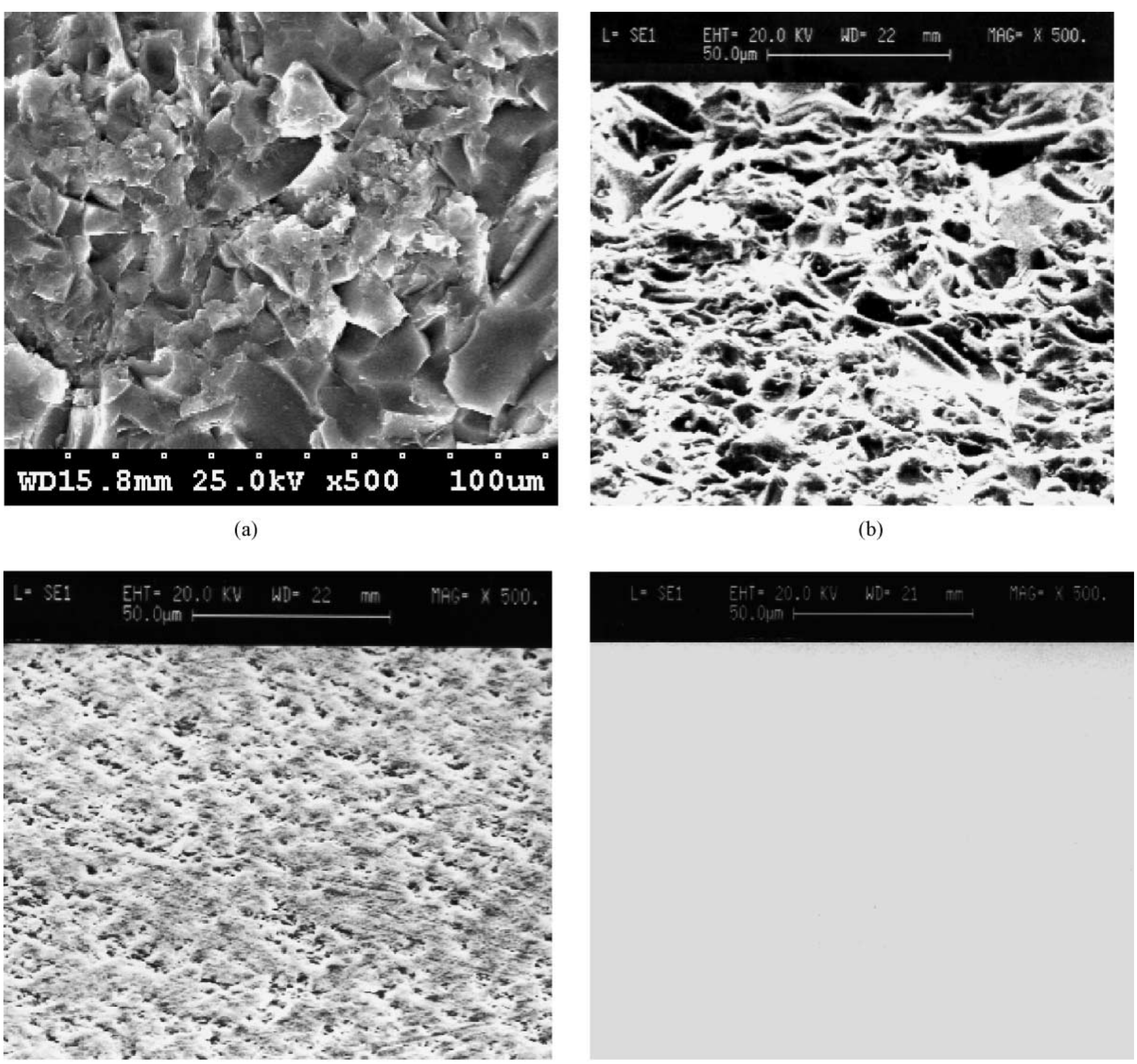
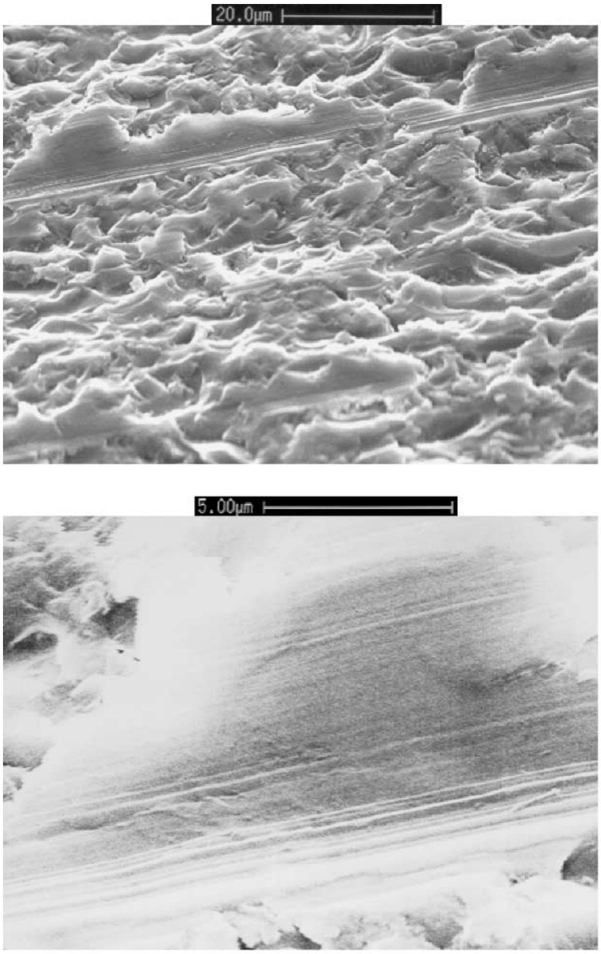


Fig. 6. SEM pictures of glass surfaces machined by: (a) AWJ turning; (b) conventional grinding; (c) lapping; (d) polishing.



(a)
(b)

Fig. 7. SEM pictures of aspherical glass surfaces: (a) ductile streaks at low magnification; (b) a magnified view of (a).

ductile grinding streaks, the polishing time was reduced by 50%, from 8 to 4 min.

ZrO_2 ground with a 125 grit diamond wheel at a grinding speed of 2400 m/min, a feed rate 24 m/min, and a depth of grinding of 0.5 µm and without cross-feed, also showed ductile streaks (Fig. 8). Plastic deformation was the major mechanism of the material removal at high wheel speeds [14]. 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 the folding of asperities.

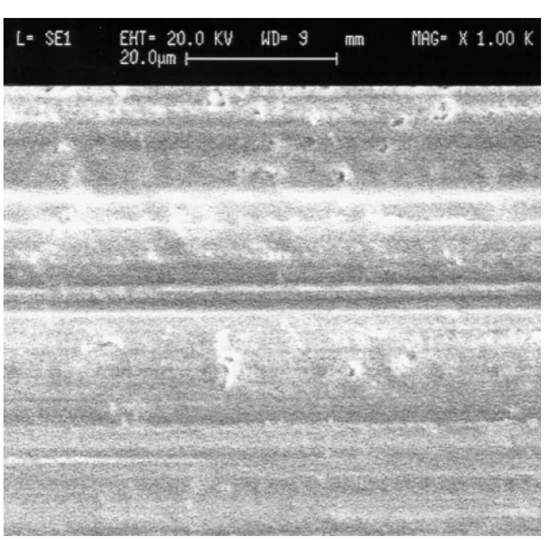


Fig. 8. Ductile streaks on ground ZrO_2.

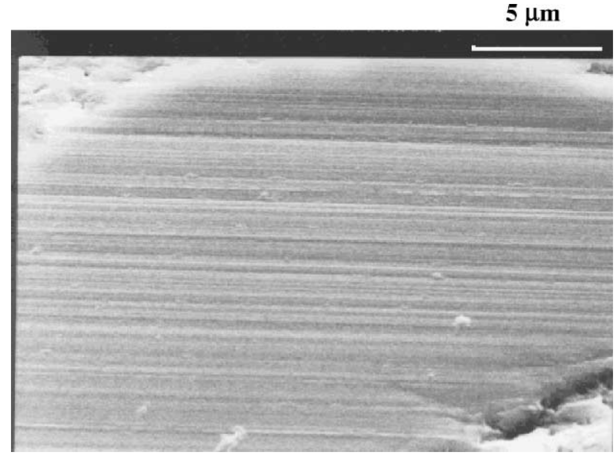


Fig. 9. An SEM micrograph of a ground MMC surface (2618/Al_2O_3/20p).

Grinding of the aluminum composite 2618/Al_2O_3 using the fine (3000 grit) diamond wheel at 1 µm in-feed (depth of grinding) produced visible ductile grinding marks on the Al_2O_3 particles (Fig. 9). Both the aluminum matrix and the Al_2O_3 particles were "cleanly" removed by the diamond grinding wheel because the ductile grinding marks were clearly seen on the Al_2O_3 particles. There were no cracks and defects found on the ground surfaces, and there was almost no sub-surface damage.

The diamond wheel also produced A359/SiC/10p-T6 surfaces with few SiC particle related defects. A very thin smearing layer of aluminum and partially hidden SiC particles were observed on fine-ground surfaces. When lightly etched with etchant, the ductile mode ground surfaces of SiC particles could be seen. As shown in Fig. 10, with an experimental depth of grinding of 0.5 µm, the ductile mode grinding of a SiC particle was observed.

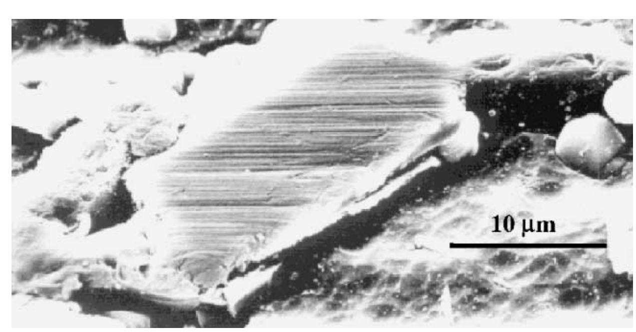


Fig. 10. An SEM micrograph of a ground MMC surface (A359/SiC/10p-T6).

4. Summary of results

Grinding using inexpensive machine tools can produce ductile streaks on glass and silicon surfaces. Under optimal grinding and lapping conditions, more partial-ductile mode surfaces could be obtained. This resulted in significantly shortened polishing time to secure an acceptable surface finish. In order to reduce the total manufacturing time, it is preferable to obtain better ground/lapped surfaces with as many ductile streaks as possible to reduce the polishing time.

Toroidal SiC surfaces ground with flat-face cup wheels indicated 100% ductile machining, and did not require polishing. Ground ZrO_2 also showed ductile streaks. Plastic deformation was the major mechanism of material removal at high wheel speeds.

Grinding of aluminum-based MMCs reinforced with Al_2O_3 or SiC particles using a 3000 grit diamond wheel at depths of grinding of 1 and 0.5 μm produced many ductile streaks on the Al_2O_3 and SiC particles, respectively. There was almost no sub-surface damage.

The machines used for the experiments reported in this paper are not expensive ultra-precision machines.

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