Acoustic emission as an indicator of material-removal regime in glass micro-machining

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Acoustic emission (AE) spectra were recorded during microgrinding of brittle materials. It was found that the specific AE energy (i.e., the measured AE energy divided by the material removal rate) was lower for fracture-dominated grinding than for plastic flow–dominated grinding. Two subsequent experiments were performed to measure AE energy while holding the material-removal rate constant. By controlling either the critical depth of cut (for ductile-brittle transition) of the workpiece material, or the actual depth of cut of the grinding machine, the sensitivity of AE energy to grinding regime was investigated for grinding with a constant material-removal rate. Contrary to conventional thinking about the relative contributions of plastic flow and fracture in generation of AE activity, it was found that the AE energy was larger in ductile-regime grinding than in brittle-regime grinding, for identical material removal rates. As a result of the experiments described in this paper, it can be concluded that AE energy measured during microgrinding is sensitive to changes in the mechanism of material removal. For a given volume of material removed, there is more AE energy in a plastic flow–dominated process than in a fracture-dominated process. The relationship found between AE energy and material removal regime could lead to an in-process sensing strategy for controlling grinding ductility.

Keywords: *ductile-regime grinding; ultraprecision machining; acoustic emission; brittle materials*

Introduction

In fixed-abrasive glass grinding processes, much recent research has been directed toward reducing the resulting subsurface fracture damage. The two benefits of reduced damage are decreases in the extent of finishing (e.g., polishing and/or lapping) processes required to achieve desired finish, and increases in the achievable contour accuracy of the component. Precision grinding on brittle materials accomplished without generating subsurface fracture damage is called ductile-regime grinding. To achieve ductile-regime grinding, there are certain principles, now well established, regarding machine accuracy, machine stiffness, environmental control, real-time feedback control of position, and critical depth of cut. The most basic requirement for maintaining a ductile material removal regime is to ensure that the depth of cut made by an individual abrasive cutting grain does not exceed some threshold value (i.e., the critical depth of cut). If the actual depth of cut made by an individual abrasive grain exceeds the critical depth of cut, fracture occurs beneath the abrasive, and the material removal mechanism changes from ductile plowing to brittle crack propagation.

Previous research has resulted in a model for the critical depth-of-cut in terms of the properties of the workpiece material:

$$d_c = 0.15 \left(\frac{E}{H}\right)\left(\frac{K_c}{H}\right)^2$$

where d_c is the critical depth of cut, E is the elastic modulus, H is the hardness, and K_c is the fracture toughness of the glass.

This model, which has been verified for various

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ceramics, glasses, and crystalline brittle materials, asserts that the mechanism of material removal depends on the cutting depth made by an individual abrasive grinding grain. If the actual depth-of-cut exceeds the critical depth-of-cut, then the material removal regime will make a transition from purely ductile cutting to ductile cutting plus fracture. As the depth of cut increases, the material removal mechanism becomes more and more dominated by fracture.[1–6]

Recently, it has been found that the critical depth of cut is also considerably affected by the grinding fluid chemistry,[7–10] as well as the wheel bond material.[11] Though it is a valuable starting point, the model does not provide enough information to determine the critical depth of cut for transition to within a factor of two. Moreover, even if the critical depth of cut were known and constant, in contour grinding the contact geometry between the grinding wheel and the workpiece is constantly changing, making it difficult to control grinding chip thickness (i.e., the actual depth of cut).

Even with these uncertainties in the abrasive grain depth of cut (both actual and critical), it is possible to grind in a ductile regime on grinding machines with sufficient precision by prescribing a conservative actual depth of cut. To improve the productivity of ductile regime grinding further, one alternative is to implement an in-process measure of grinding ductility, to be used as feedback to control the actual depth of cut. Such an in process control signal could be used to expand the operating envelope of a ductile regime grinding machine.

Acoustic emission has been found to be sensitive to small changes in grinding regime. It will be shown that the conventional thinking about the relative intensity of AE from fracture and plastic flow is incorrect for microgrinding with a constant material-removal rate. Specifically, the experimental results presented here suggest that for a given material removal rate, AE energy in fracture-dominated grinding is considerably smaller than AE energy in plastic flow–dominated grinding.

The sensitivity of AE energy to grinding regime could be exploited as a feedback signal for real-time control of ductile regime grinding.

Background

Acoustic emissions are elastic waves generated by abrupt localized changes in the stress in a solid. These waves travel to the surface of the solid, where they can be detected by a piezoelectric transducer. In material removal processes, AE signals are due to either fracture or plastic flow. Because elastic waves propagate with frequencies from 100 kHz to 2 MHz, well above most structural natural frequencies, machine vibrations will not influence the AE signal. Acoustic emissions are therefore ideal for characterizing material removal activity. Recently, a number of Japanese and Soviet researchers have begun scientific investigations of AE signals generated in precision grinding of glass and ceramics.[12–15] Their results indicate that it is possible to monitor and control subsurface damage in ceramics using AE feedback to the grinding machine. Other researchers have developed techniques to monitor grinding wheel trueing and dressing using AE, thereby ensuring repeatable wheel performance in grinding processes.[16,17]

In many previous studies, it has been demonstrated that the amplitude of AE energy due to the sudden propagation of a crack is much larger than the amplitude of AE energy immediately preceding crack propagation. For example, in a single point turning study at the National Institute of Standards and Technology,[18] it was found that machine processes producing continuous plastic chips resulted in a continuous, low-level AE signal emanating from the shear zone and the chip/tool interface. Upon fracture of the chip, a high-amplitude AE burst was observed, indicating effective chip breaking. The ratio of chip-breaking AE amplitude to the AE background signal amplitude was found to be material dependent, with a larger ratio found to correspond to harder materials.

AE energy differences have also been used to monitor the onset of brittle fracture in micromachining processes on brittle materials. In one study, the effect of coolant on surface ductility in hard materials was examined for a constant-load diamond drilling operation on glass.[19] It was found that the AE energy associated with this process could be used as a sensitive diagnostic tool. A larger AE energy resulted from drilling processes in which the dominant material removal regime was fracture (large load), as opposed to plastic flow (small load).

A logical extension of such experimental results has been the generally accepted rule that in cutting, AE energy generated by fracture-dominated processes is larger than AE energy generated by plastic flow–dominated processes, leading to the expectation that brittle regime machining would produce more AE energy than ductile regime machining. In this article, it will be demonstrated that this generalization is incorrect. In fact, it will be shown that for a given volume of material removed from a given brittle material, the AE energy for fracture-dominated machining is considerably lower than the AE energy for plastic flow–dominated machining.

AE in glass microgrinding

In previous work by Bifano et al.[11,20] AE signals were monitored for both germanium and soda-lime glass samples machined in a plunge grinding operation with grinding infeed rates from 2 to 150 nm/revolution. The grinding parameters that were used in the study are presented in *Table 1* (further descriptions of the apparatus are available in ref. 1). It is important to note that in plunge grinding, the grinding

Table 1 Machining conditions for plunge grinding tests on germanium and soda-lime glass

Configuration	100 mm diameter 6 mm wide cup wheel, plunge grind
Wheel type	4–8 μm natural diamond, bronze bond, concentration 50
Wheel preparation	6 μm diamond paste trueing and dressing
Workpiece	5 mm × 5 mm × 25 mm, glued (cyanoacrylate) to chuck
AE sensor	82 g, 41 mm diameter, 25 mm height, mounted to chuck
Infeed axis	Clamped flexure, piezoelectric stack actuator
Infeed control	2 nm resolution, closed-loop (PI), 10 Hz bandwidth
Machining conditions	Constant velocity infeed, 2–150 nm/revolution
Wheel speed	500 rpm
Grinding coolant	Deionized water

Table 2 AE system description and data collection procedure for germanium and soda-lime glass plunge grinding

Hardware	
AE sensor	Bruel & Kjaer Model 8312 (integral preamplifier)
Postamplifier	Bruel & Kjaer Model 2638 (20 dB gain)
Band-pass filter	100–1,000 kHz
Sensor average sensitivity	70 V/(m/s) (output voltage/surface velocity)
Sensor sensitivity range	(100 kHz – 1 MHz) ± 10 dB
A/D conversion	2.5 MHz sampling rate, 8-bit resolution
Signal processing	*Off-line, Vax workstation*
Data collection procedure	
6 grinding tests	Germanium & Glass: 3, 30, and 150 nm/revolution infeeds
Sampling rate	2.5 MHz
Samples per frame	128
Frames per test	6
Fourier transform	128 point FFT, Hanning window
Averaging	6 energy spectra averaged for each test
Frequency resolution	20 kHz

infeed rate, the actual depth of cut, and the material removal rate are all directly proportional to one another.[1]

For each plunge grinding test, the grinding infeed rate was fixed, and AE signals were monitored by an automated data collection system. The AE system components and data collection protocol for these plunge grinding experiments are listed in *Table 2.*

The AE power spectrum was obtained via fast Fourier transformation of the raw AE data. Because the voltage output of the sensor has been calibrated by the manufacturer (ASTM E1106-86, standard method for primary calibration of AE sensors) in terms of the surface velocity at the workpiece sensor interface, the power spectral density coefficients of the "power spectrum" computed by Fourier transforming the sensor output have dimensions of velocity squared per frequency. The power spectrum permits an evaluation of both the amplitude and frequency content of the AE signals generated during microgrinding.

An example of an AE power spectrum is illustrated in *Figure 1* for germanium ground at a 3 nm/revolution infeed rate. The vertical axis (i.e., power spectral density) includes scaling of the analog AE sensor output voltage by the sensor's average sensitivity (70 V/(m/s)) and the AE amplifier gain.[10] The peak in this spectrum relates to AE activity during material removal. A measure of the integrated spectral power density surrounding the peaks (e.g., from 100 kHz to 1,000 kHz) is indicative of the AE energy of the process. (Because spectral power has dimensions of velocity squared, spectral power is proportional to the AE kinetic energy.) It is important to note that all AE activity is not due to chip formation and fracture: some AE energy is generated by plowing and rubbing even when there is no material removal.

For both germanium and soda-lime glass, the AE energy (power spectral density integrated from 100 to 1,000 kHz) increases significantly with increases in the material removal rate (*Figure 2*). Because sensor placement and elastic transmission

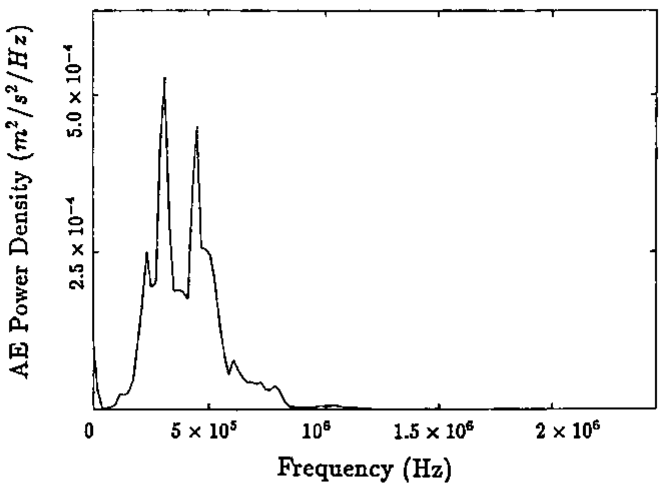

Figure 1 Acoustic emission power spectrum for germanium microgrinding

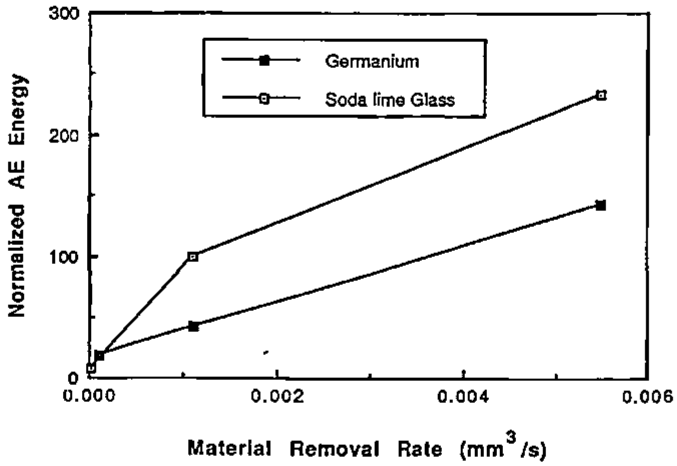

Figure 2 Normalized AE energy as a function of the material removal rate in plunge grinding

properties of the workpiece and workpiece holder affect the amplitude of the AE signal, we interpret AE power spectra with respect to a reference spectrum, as follows. In all experiments described in this article, the AE energy is measured by integrating the power spectral density over a frequency range of 100 to 1,000 kHz. Normalized AE energy refers to the measured AE energy of a particular grinding test, divided by the AE energy measured with the sensor in place, the workpiece mounted, and the grinding wheel spinning, but before any grinding contact. Variations in sensor sensitivity (±10 dB) at different frequencies make physical interpretation of the ordinate of the power spectrum difficult. However, if two spectra are obtained using the same experimental setup, the relative change in AE energy can be measured.

After grinding, the area percent of surface fracture was determined for each sample at each material removal rate, using scanning electron microscope photographs of the ground surface, in a method that has been described previously.[11] It was found that the actual depths of cut spanned by these experiments encompassed the critical depth of cut for both of these materials. That is, at the lower material removal rates (e.g., small infeed rate), both materials had almost no residual fracture damage, whereas at the higher material removal rates, both materials had more than 10% of their surface area covered with fracture. *Figure 3* is a plot of the normalized AE energy versus the measured area percent of surface fracture for both germanium and soda lime glass.[11] A nearly linear dependence between normalized AE energy and surface fracture was found for both soda lime glass and germanium, although the slope differs for the two materials. The increased AE energy can be attributed to either one or both of two effects: a transition from ductile to brittle material removal or an increase in the material removal rate. An indirect way to determine the effect of the ductile-brittle transition on AE energy is to divide the AE energy measured for each grinding test by the material removal rate for that test, producing what might be called the specific AE energy. *Figure 4* is a graph of specific AE energy plotted as a function of material removal rate. *Figure 5* compares specific AE energy to the measured surface fracture damage. Here, an unequivocal decrease in the specific AE energy occurs as surface fracture increases.

Dividing the AE energy by the material removal rate may not be strictly valid as a technique for separating the two potential causes (i.e., the ductile-brittle transition and increased material removal rate) for increased AE energy. However, the results of this preliminary test indicate that, all other factors being equal, the net result of a ductile-brittle transition in material removal rate may be to decrease the AE energy. The results presented in the next section support this hypothesis.

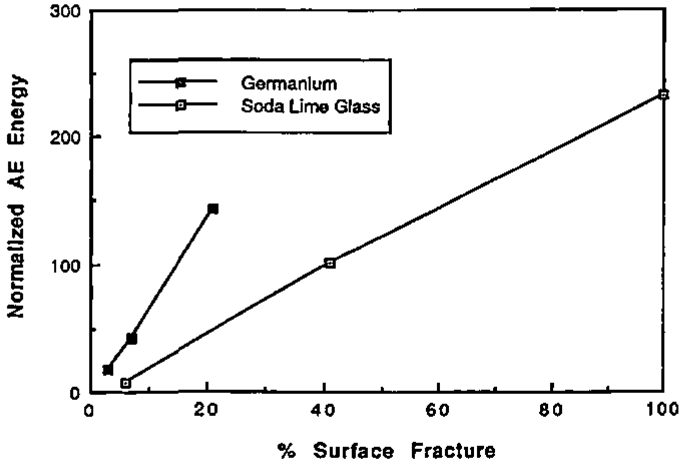

Figure 3 Normalized AE energy versus grinding ductility in plunge grinding

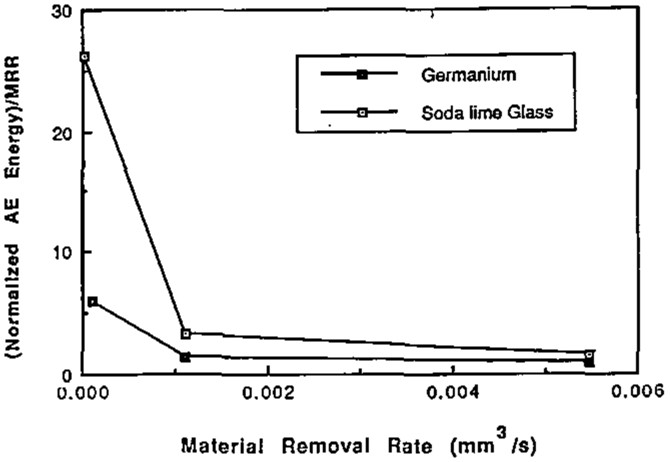

Figure 4 Specific AE energy as a function of material removal rate in plunge grinding

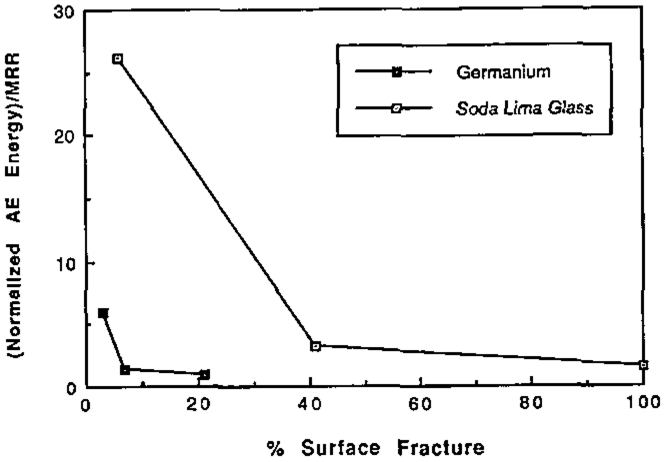

Figure 5 Specific AE energy as a function of grinding ductility in plunge grinding

AE energy and the ductile-brittle transition

In a more recent experiment, a combination of chemomechanical effects and AE allowed us to analyze AE power spectra from a single workpiece subjected first to ductile regime grinding conditions and then to brittle regime grinding conditions at the same material removal rate. In these experiments, the AE data collection system was significantly refined to provide greater spectral resolution in both frequency and amplitude.

Chemomechanical effects in glass microgrinding have a strong influence on the surface properties of the workpiece material. Recently, it has been demonstrated that the surface charge on the solid (measured as ζ-potential, the charge in the liquid boundary layer) may influence the resistance of the surface to fracture. Specifically, it was found that when $\zeta \sim 0$, glass materials exhibit increased surface toughness. The importance of chemomechanical toughening of the surface is that it can influence the material removal mechanism in microgrinding by altering the material's critical depth of cut for fracture initiation.

The relationship between d_c and K_c is such that chemomechanical toughening will increase the critical depth of cut, resulting in enhanced grinding ductility (or inhibited grinding fracture) for a fixed actual depth of cut. Consequently, chemomechanical effects make it possible to alter the grinding regime without changing the material removal rate. In recent papers by Golini et al.,[7–10] it was demonstrated that under certain grinding conditions on a precision grinding apparatus, it is possible to achieve 100% ductile regime grinding on ULE (titania doped fused silica glass made by Corning) glass workpieces in a heptanol environment. Under the same grinding conditions in a water environment, the surface of the workpiece was entirely fractured, indicating 100% brittle regime grinding. This experiment provides an ideal setting for the analysis of acoustic emission and its relationship to the ductile-brittle transition in microgrinding.

ULE glass samples were ground on an ultraprecision surface grinding apparatus. *Figure 6* is a schematic of the apparatus. In this configuration, the workpiece is mounted on an air-bearing linear slideway, which is used as a cross-feed mechanism. The grinding wheel is cup shaped, and mounted on an air-bearing spindle with its rotational axis oriented perpendicular to the cross-slide axis. Both the cross-feed axis and the infeed axis are controlled in real time with a resolution of ~ 5 nm. For the cross-feed, this is accomplished using a piezoelectric "inchworm" actuator, with a range of 50 mm. Infeed of the workpiece into the grinding wheel is accomplished using a fast piezoelectric actuator, controlled in real time within a 300 Hz bandwidth by closed-loop feedback from a capacitance gauge. The measured static stiffness of the grinding contact (in the infeed direction) is 50 MN/m. Further details of the apparatus are reported elsewhere.[21] The grinding apparatus specifications in general and the grinding conditions used in these grinding tests in particular are summarized in *Table 3.*

Before grinding, the diamond grinding wheel

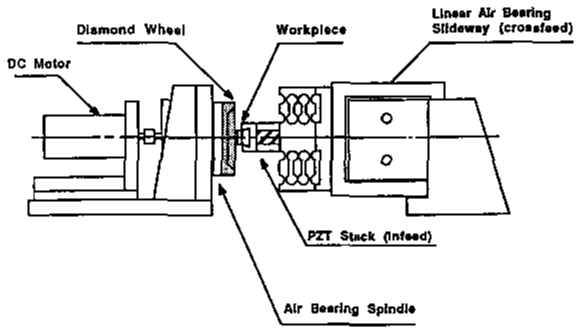

Figure 6 Schematic of the two-axis microgrinding apparatus

Table 3 Machining conditions for microgrinding tests on ULE glass

Wheel geometry	100 mm diameter, 6 mm wide cup wheel (6A2, Norton)
Wheel type	4–8 μm natural diamond, resin bond, concentration 75
Wheel preparation	Single-point diamond dressing
Workpiece	5 mm × 5 mm × 25 mm, glued (cyanoacrylate) to chuck
AE sensor	8 g, 3.6 mm diameter, 2 mm height, mounted to the chuck
Crossfeed axis	Air-bearing piezoelectric inchworm actuator (5 nm resolution)
Infeed axis	Flexure, piezoelectric stack actuator
Infeed control	5 nm resolution, closed-loop (PID), 300 Hz bandwidth
Machining conditions	Fixed infeed step, constant velocity crossfeed
Infeed	500 nm fixed infeed per crossfeed pass
Crossfeed	33 μm/s
Wheel speed	1,500 rpm
Grinding coolant	Deionized water or 1-heptanol

was dressed once. The ULE sample was ground flat on a commercial surface grinder before being mounted on the microgrinding apparatus. After mounting, the ULE sample was prepared for AE tests by grinding to a depth of 10 μm from the original workpiece surface, using the grinding conditions specified in *Table 3*, with water as the grinding coolant.

After this preparation, an AE sensor was fixed to the workpiece chuck (with a petroleum jelly interface), permitting collection of AE signals during grinding. The AE data collection system is illustrated schematically in *Figure 7*. The prepared ULE workpiece (still mounted on the microgrinding apparatus) was subjected to a final crossfeed pass, with a fixed 500-nm infeed. Halfway through that pass across the workpiece, the coolant was abruptly changed from water to heptanol. All other machining conditions, including material removal rate, remained constant. From the chemomechanical hypothesis and experiments described previously,[7] it has been established that, for these grinding conditions, this coolant change will result in a transition from predominantly brittle regime grinding to predominantly ductile regime grinding. During the first half of the last grinding crossfeed pass (with water coolant), 32 sequential AE waveform frames, each of 4,096 data points sampled at 2.0 MHz, were recorded, Fourier transformed, averaged, and stored as a single test. This was all done in real time, using a high-speed data acquisition and processing system. The same data collection process was repeated for the last half of the crossfeed pass (with heptanol coolant). The results of these two tests, made during a single pass of the grinding wheel, were subsequently analyzed to determine the influence of the changed grinding conditions on the AE spectrum.

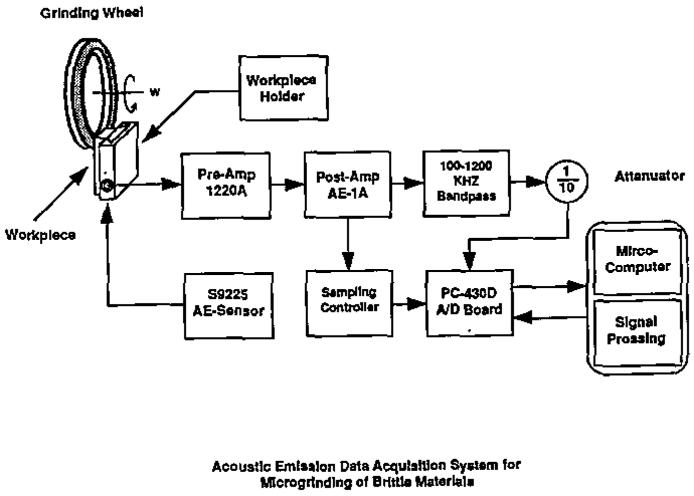

Figure 7 Schematic of AE data collection system

Table 4 summarizes the AE system and the data collection procedure.

This data collection system has 40 times better frequency resolution and 16 times better amplitude resolution than the system described in *Table 2*, which was used in previous experiments.

In addition to the AE power spectrum, the grinding tangential force was measured during both grinding tests to determine the specific grinding energy. The procedure for this measurement has been described previously.[22] It was found that grinding in heptanol, which produces less damage for the same material removal rate than grinding in water,[7] resulted in higher specific grinding energy. The correlation between decreasing fracture damage and increasing specific grinding energy is in line with results from previous research on microgrinding of brittle materials.[22]

Contrary to conventional wisdom, however, it was found that the AE energy (the integrated power spectral density from 100 to 1,000 kHz) was three times as large in ductile grinding (heptanol environment) than in brittle grinding (water environment), for identical material removal rates (*Figure 8*). The ordinate axis of the power spectrum is normalized by the peak AE power spectral density measured before grinding contact.

Table 4 AE system description and data collection procedure for ULE glass and single-crystal quartz surface grinding

Hardware	
AE sensor	Physical acoustics model S9225
Preamplifier	Physical acoustics model 1220A (60 dB gain)
Postamplifier	Physical acoustics model AE1A (40 dB gain)
Band-pass filter	100–1,200 kHz
Sensor peak sensitivity	250 V/(m/s) (output voltage/surface velocity)
Sensor sensitivity range	(100 kHz − 1 MHz) ± 13 dB
Computation	80386 microcomputer, 33 MHz
A/D board	Datel PC430D, 4 MHz sampling rate, 12-bit resolution
Signal processing	PC430D uses an integral TMS320C30 processor
Control software	Hypersignal workstation
Data collection procedure	
4 grinding tests	ULE, in water/heptanol; quartz, 2,760 rpm, 2,000 rpm
Sampling rate	2 MHz
Samples per frame	4,096
Frames per test	32
Fourier transform	4,096 point FFT, Hanning window
Averaging	32 power spectra averaged for each test
Frequency resolution	500 Hz

In some prior studies of the relationship between material removal mechanism and AE energy,[23] the machining load was kept constant, and material removal rate increases were found to correspond with larger acoustic emission energy and a transition to brittle regime grinding. Unfortunately, these data were not modified to account for the increasing material removal rate that accompanied the transition from ductile regime machining to brittle regime machining. However, it appears from the results presented here that when the material removal rate is held constant, ductile regime grinding emits significantly more AE energy than brittle regime grinding.

It has been suggested that the increased AE energy observed in a heptanol environment may still correspond to increased fracture activity, even though the ground surface appears less fractured.[24] Specifically, it has been proposed that as a result of surface chemistry changes, the grinding chip produced in a heptanol environment may contain considerably more microfracture (e.g., small cracks ahead of the tool/work interface that relieve stress but are too small to contribute to material removal) than the grinding chip produced in a water environment. Because the chip is removed in the cutting operation, it is possible that this microfracture would not extend into the material surface, but would be carried away with the grinding chip. Conversely, in the water environment, it is possible that such microfracture does not occur, but that fewer, larger cracks are produced, extending deep into the material surface.[24] In this way the heptanol environment could be producing more fracture events, even though it results in a more damage-free surface.

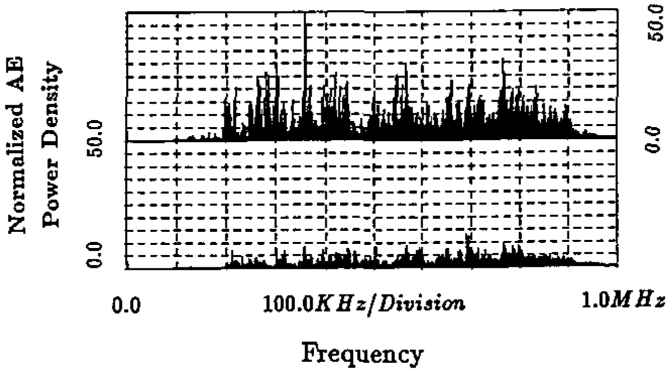

Figure 8 Acoustic emission power spectra for constant material removal rate microgrinding of ULE glass: top, in heptanol; bottom, in water

To explore this possibility, AE signals were recorded and Fourier transformed during the grinding of single-crystal quartz in a water environment under conditions that would result in an intermediate (~25%) amount of surface fracture. Quartz was used in this experiment instead of ULE because its AE power spectrum is sharply peaked and centered around a single frequency, allowing a more sensitive measure of changes in AE peak power spectral density and AE energy in response to small changes in machining conditions. The ultraprecision surface grinding apparatus (*Figure 6*) was used for these experiments. The grinding conditions, selected to achieve a moderate amount of grinding fracture, are summarized in *Table 5*. While maintaining a constant material removal rate, the grinding wheel

Table 5 Machining conditions for microgrinding tests on single-crystal quartz

Wheel geometry	100 mm diameter, 6 mm wide cup wheel (6A2, Norton)
Wheel type	60–80 μm natural diamond, bronze bond, concentration 75
Wheel preparation	Single-point diamond dressing
Workpiece	30 mm × 30 mm × 0.15 mm, quartz, vacuum chucked
AE sensor	8 g, 3.6 mm diameter, 2 mm height, mounted to the chuck
Crossfeed axis	Air-bearing, piezoelectric inchworm actuator (5 nm resolution)
Infeed axis	Flexure, piezoelectric stack actuator
Infeed control	5 nm resolution, closed-loop (PID), 300 Hz bandwidth
Machining conditions	*Fixed infeed step, constant velocity crossfeed*
Infeed	200 nm per crossfeed pass
Crossfeed	1 μm/s
Wheel speed	2,670–2,000 rpm
Grinding coolant	Deionized water

speed was reduced by 25%, from 2,670 rpm to 2,000 rpm. The effect of this wheel speed reduction was to increase the actual depth of cut (i.e., chip thickness) made by each abrasive grain, while maintaining a constant overall material removal rate. Assuming a fixed critical depth of cut for the material, an increase in the grinding chip thickness will result in more fracture and more subsurface damage.[1,5] AE power spectra were recorded using the equipment and procedures described in *Table 4. Figure 9* illustrates the results of this experiment. A 50% reduction in AE energy accompanies the 25% increase in actual depth of cut (chip thickness). Again, the result supports the hypothesis that there is more AE energy in ductile regime grinding than in brittle regime grinding for a given material removal rate.

Discussion

The dependence of AE energy on material removal regime for brittle materials might be related to the number of bonds that must be broken to remove material. Because AE measured at the surface is the direct result of atomic bond activity (the source of AE elastic waves), the empirical evidence presented in this paper indicates that there is more (or at least more coherent) bond-breaking energy in ductile grinding than in brittle grinding. A parallel argument has been made regarding specific grinding energy.[22] An analytical model was developed for specific grinding energy in microgrinding. This model predicted larger specific grinding energy in ductile material removal than in brittle material removal. A series of microgrinding experiments confirmed the general applicability of the model for brittle materials.

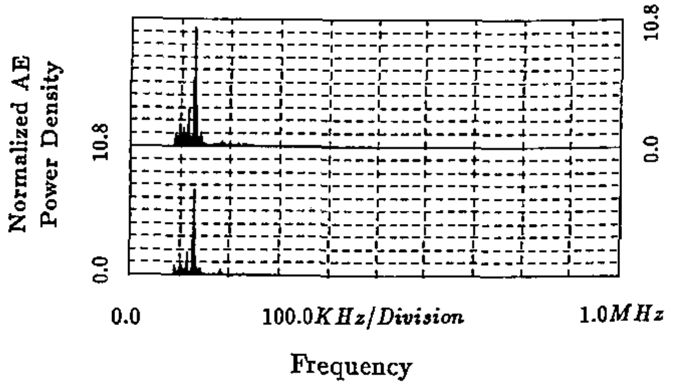

Figure 9 AE power spectrum for grinding of monocrystalline quartz, with a constant material removal rate: top, smaller actual depth of cut; bottom, larger actual depth of cut

Acoustic emissions are abrupt releases of elastic energy that result when bulk material is deformed and/or fractured. The source of acoustic emission could include moving dislocations, crack nucleation and propagation, grain boundary sliding, fracture and decohesion of inclusions, and phase transformations.[25] Not all of these mechanisms are active in all brittle materials.

In microgrinding, each protruding abrasive diamond grain will generate an intense local stress field on contact with the workpiece material. This energy must be released one way or another, in the form of either plastic flow or crack propagation, both of which can result in acoustic emission. Also, the plastic deformation itself will cause a residual stress field after the passage of the abrasive grain, which may result in further crack propagation and AE activity.

In grinding crystalline brittle materials, dislocation motion and crack growth are primary sources of AE. Moreover, the AE wave detected at the material surface contains information about both the location and the characteristics of the source.[26–28]

Dislocation motion and acoustic emission

From the experiments described in this article, it is apparent that AE energy resulting from plastic flow is significant. Some previous research has been directed toward understanding the relationship between dislocation motion and AE generation.[29] An important result of that research was the discovery that 99% of the energy generated by dislocation motion is dissipated as heat, leaving only 1% of the energy to take the form of an elastic wave that could be detected by an AE sensor.

Acoustic emission resulting from dislocation motion can be attributed largely to relaxation of the elastic stress field in the lattice caused by the passage of the dislocations and/or annihilation of dislocations.[29] Detectable acoustic emission requires coherence of dislocation motion; i.e., a relatively long length (up to 2 m) of dislocation line must move almost simultaneously within a small volume of bulk material for enough energy to be released to result in a signal strong enough for piezoelectric detection at the material surface.[29,30] Two mechanisms have been proposed for the massive coherence of dislocation motion that is associated with detectable acoustic emission. In the first possible mechanism, a pinned dislocation line that is subjected to an increasing shear stress eventually breaks free of its pinning point. Once released, the dislocation causes a small stress wave, which adds to the shear stress on nearby pinned dislocations, freeing them in what becomes a self-perpetuating avalanche of dislocation motion. The second proposed mechanism depends on the existence of Frank-Read sources, where many dislocation loops can be generated and propagated rapidly.

Although the relationship between dislocation motion and AE has been the focus of considerable study, it is difficult to apply these results directly to microgrinding. The quartz samples that were ground in the experiments described in this article were monocrystalline, and could be treated with classical dislocation theory; however, ULE is fused silica, containing a small fraction (~7.5%) of titanium dioxide, and is amorphous. For amorphous materials, the dislocation mechanisms described previously are not directly applicable.

For a crystalline material, the number of dislocations generated by an abrasion process scales with the size of the plastic zone generated beneath the surface of the material.[31] In single-point, ductile regime grinding, the volume of the plastic zone beneath a sliding abrasive grain increases with the abrasive grain depth of cut, leading one to expect increased AE activity for an increase in material removal rate. If the actual depth of cut is increased beyond that required for purely ductile regime grinding, then lateral and median cracks will occur beneath the abrasive grain. At this point the AE energy is due to both dislocation motion and fracture. Although the size of the plastic zone continues to grow in brittle regime grinding (leading to more dislocation-induced AE energy), the material removal rate increases as well, resulting in an overall reduction in AE energy for a given volume of material removed. Even the addition of coherent AE energy due to the fast propagation of median and lateral cracks appears to be insufficient, when divided by the material removal rate, to equal the specific AE energy of ductile grinding.

Conclusions

As a result of the experiments described in this paper, it can be concluded that AE energy in microgrinding brittle materials is directly related to the mechanism of material removal. For a given volume of material removed, there is more AE energy in a plastic flow–dominated process than in a fracture-dominated process. This relation parallels the one found between specific grinding energy and material removal regime: ductile regime grinding requires more specific energy than brittle regime grinding.

It is conceivable that the relationship between specific acoustic emission energy and material removal regime could be exploited to provide in-process control of grinding ductility. However, such an implementation would require dividing the detected AE energy by the material removal rate. It would be more feasible to find correlations between the AE signal and the material removal regime that were independent of material removal rate. One such correlation, between acoustic emission power spectrum signature and material removal regime, is currently under investigation.

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