Acoustic Emission and Deformation Mode in Ceramics During Indentation*

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Acoustic emission (AE) monitoring was carried out during indentation tests of ceramic materials to reveal different types of emission and to correlate them with microscopic observation in order to identify plastic deformation or cracking phenomena. The results show good correlation between the AE characteristics and deformation mode of ceramics below the diamond indenter. The AE generated by surface cracks are of higher amplitude, longer duration and higher frequency, compared with the phenomenon during plastic deformation. Consequently, deformation processes of ceramics are distinguished by AE signal analysis. Moreover, this monitoring method is effective in examining the threshold load for cracking.

Key Words: Ceramics, Acoustic Emission, Indentation, Plastic Deformation, Crack

1. Introduction

The machining process of fine ceramics is a complicated process which is usually carried out using abrasive machining. Because of the great hardness of ceramics, the most common abrasive is diamond grains. The machining method can be polishing, lapping or grinding. However, in all of these abrasive methods, *indentation* can be used as a very simple model for understanding the deformation and removal mechanics of a workpiece. Indentation of brittle materials produces idealized model flaws. Study of such flaws provides valuable insight into the mechanism of failure due to surface damage in brittle materials.

On the other hand, micromechanical deformation processes such as plastic deformation and crack nucleation which occur during abrading of ceramics by

diamond grit, are sources of *acoustic emission* (AE). In order to use AE signal processing for in-process detection of the machining process of fine ceramics, it is very important to study the characteristics of the signals from the impact of a small diamond particle upon the surface of engineering ceramics. There are many types of noise during a real machining process, such as grinding fluid noise and grinding wheel noise. These types of noise can only be eliminated through a combination of sufficient information about abrading signals and skillful interpretation of data. The indentation process is a calm and noise-free process, thus the generation of each acoustic signal can be related to one particular mechanical event in the ceramic material. Currently, there appears to exist no comparable experimental data concerning acoustical characteristics of ceramics during plastic deformation and cracking. In a few published works, AE was used for monitoring the indentation of ceramics. In 1979, Lankford and Davidson⁽¹⁾ used AE signals and SEM observation to predict of the threshold load for which the mode of material changes from plastic deformation to cracking. However their experimental conditions were such that only signals with values greater than

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the crack nucleation threshold could pass the discrimination level to generate AE events. Under such conditions where AE was generated, they observed only radial cracks, thus they suggested that for alumina and some other ceramic materials, threshold cracking is related to radial rather than median cracking. Sperisen et al.⁽²⁾ used acoustic emission and controlled indentation methods to understand the microfracture behavior of alumina. Unlike Lankford and Davidson, they reported that no threshold of loading can be identified (given their 0.01 N minimum detectable load) below which there would be no acoustic activity. This means that there is some AE activity during plastic deformation of alumina, even though they did not distinguish between plastic mode and cracking using AE specifications.

In this study we considered the differences between the AE parameter specifications, i.e., amplitude, frequency, duration and oscillations corresponding to the plastic mode of deformation and cracking phenomena, as well as the influence of crack type in AE signals for a given ceramic. In particular, we are interested in knowing the AE characteristics of plastic deformation which is the predominant mechanism in ductile-mode grinding, and its differences with signals from cracking in brittle-mode grinding.

2. Experimental Procedure

The material used for indentation was a normal sintered alumina (obtained from Fine Ceramic Center). Table 1 shows the mechanical properties of this ceramic. It was cut to appropriate sizes for attaching the AE sensor and for scanning electron microscopy (SEM). Both faces of the specimens were highly

Table 1 Mechanical properties of workpiece
(Wt% 99.7 Al₂O₃)

Property	Amount	Unit	Measuring method
Bending strength	347	MPa	JIS R1601, 4-point bending test, room temp.
Hardness	1590	HV10	Vickers, 10 kg
Fracture toughness	4.5	MPa ^{1/2}	SEPB, JIS R1607
Density	3.92	g/cm ³	Archimedes
Average grain size	0.4	μm	Before sintering (AES-11E)
	1.9	μm	After sintering
Thermal conductivity	32.2	W/mk	Laser flash

Fig. 1 The mechanism for controlling depth of indentation

polished. A universal Vickers microhardness tester with a constant-dead-load system was used to apply the indentation load.

Indentation experiments were performed by two different methods. The first method was similar to the standard method of hardness testing in which the maximum load on the indenter was varied (10, 50, 100, 200, 300 and 500 N). In the second method, the depth of penetration was controlled using a stopper to generate a very small plastic impression (Fig. 1). The height of the stopper could be varied so that a crack-free impression was gained. After each indentation, the size of the Vickers impression and crack length if any, were measured using the microscope of the hardness tester. A Kistler dynamometer (type 9021) placed on the table of the tester, using a charge amplifier, transformed the indentation load into electric signals. A tube-shaped spacer (Fig. 2) protects the AE sensor from loading and transfer of the load from the specimen to the dynamometer.

The AE measurement apparatus and data processing system described in a previous study⁽³⁾ was used (NF Corporation). Figure 2 shows the block diagram of this assembly. The acoustic emission signal was detected using a piezoelectric transducer of 140 kHz resonance frequency which was attached to the opposite side of indentation on the workpiece using a wax-type couplant. Then the detected signal was passed through a low-noise preamplifier with 40 dB gain and through the main amplifier for a total gain of 60 dB. To detect the full signal, we tried to eliminate the background noise using a discrimination level slightly higher than the noise level. The background noise level in these experiments was very low, thus a discrimination level of 0.2 V was sufficient to eliminate noise. In some experiments, a high-pass filter with cut-off frequency of 100, 200, or 500 kHz was used.

Fig. 2 Experimental setup for indentation

Fig. 3 Time history of indentation load, AE average amplitude and cumulative event count

3. Results

Before considering the acoustic emission results in detail, it was necessary to show that the acoustic activity was only generated by deformation of the specimen rather than by the hardness tester equipment. To check this, the equipment was loaded and unloaded when there was no contact between the indenter and the specimen. During this test AE was not generated, therefore it is reasonable to conclude that the acoustic emission is generated only by the specimen during plastic deformation and cracking.

3.1 Time history of load and AE amplitude

In-process recording of load and AE average amplitude (sampling time: 1.5 ms) provided the first visible (on-line) data of the experiments. Figure 3 shows one example of these records. The maximum AE activity occurred while the loading rate increased. When the load on the indenter was kept constant, AE events were not generated. There is a good similarity between the loading curve and the cumulative event curve in Fig. 3. During unloading, the load on the indenter decreased but AE events were generated. However, when the depth of indentation was very small using the stopper, the impression was completely plastic and no AE activity was observed during unloading. Thus the high-amplitude AE events near the end of unloading, must be related to lateral crack initiation.

3.2 Microscopic observation

Immediately after each indentation test, the surface of the workpiece was examined using the microscope of the hardness tester and the impression size and the crack length were measured. When the depth-controlling stopper was used, the impression was plastic without surface cracks. The results of load measurement showed that even for indentation load of 10 N, radial cracks could not be observed. According to Cook and Pharr's observations⁽⁴⁾, during loading of alumina, only radial cracks can initiate and propa-

Fig. 4 Indentation crack length ratio c/a vs indentation load

Fig. 5 Dependence of AE event count rate on indentation load

gate, thus any AE activity before the generation of radial cracks must be caused by plastic deformation. The experimental results show that for higher loads, the surface cracks at the corners of the impression were visible. The ratio of crack length c/a (Fig. 4) increased with increasing indentation load, as expected.

3.3 AE event counting

The variation of AE event rate with indentation load is illustrated in Fig. 5. The cumulative AE event count also increased with increasing load, because the damage size increased. In these experiments the

loading rate depended on the amount of dead load. Thus in Fig. 5 the increase of the AE event rate vs. load is mainly due to increasing loading rate.

A question is whether the number of AE counts per unit load (total count/indentation load) is the same for different loadings or not. Figure 6 illustrates the answer to this question. This plot indicates that more cracks per unit load are generated if the maximum load increases.

For a quantitative comparison of AE characteristics of events generated during indentation of different loads, the percentage of high-amplitude events (>4 V), long duration (>1000 μ s) and high oscillation (>120 counts/event) were calculated at each indentation load (Fig. 7). An increase of the indentation load causes larger surface flaws. According to Fig. 7, all the AE parameters increased with increasing load. Therefore it can be concluded that surface cracks of ceramics can be characterized by high-amplitude, long-duration and high-oscillation AE events.

Amplitude distribution plots of AE events in the first stages of loading (<0.4 N), when the surface below the indenter was undergoing local plastic defor-

Fig. 6 AE event counts per unit indentation load vs indentation load

Fig. 7 Percentage of AE events of higher amplitude (>4 V), longer duration (>1000 μ s) and higher oscillation (>120 count/event) at each indentation load

mation, were calculated and plotted against time in a three-dimensional graph (Fig. 8). This graph indicates that the initial events related to the first contact and start of penetration of the indenter into the ceramic are of low amplitude. Therefore increasing the depth of penetration will cause higher-amplitude events. Similarly, duration distribution and oscillation distribution graphs vs time (Figs. 9 and 10) confirm that when the material deformation is in the plastic mode, only short-duration, low-amplitude AE events are generated. These results are in agreement with the results presented by Dalgleish⁽⁵⁾ and Cuthrell⁽⁶⁾ who used amplitude distribution in their studies. They suggested that a distinct peak at higher amplitude may be characteristic of the fracture of the ceramics and brittle material studied.

3.4 AE power spectrum

The *power spectrum* or *frequency spectrum* which

Fig. 8 Amplitude distribution of AE events vs time for the first stages of loading

Fig. 9 Duration distribution of AE events vs time for the first stages of loading

Fig. 10 Oscillation distribution of AE events vs time for the first stages of loading

Fig. 11 Typical comparison between AE waveforms generated during the first stage of loading (plastic deformation), loading and unloading cycles of indentation test of alumina

shows the contribution of each frequency component to the total power of a random waveform was also examined as a technique for AE signal analysis. Typical waveforms and corresponding power spectra of acoustic emission recorded at different stages of the indentation cycle are shown in Figs. 11 and 12. The waveform of AE signals emitted at the first plastic contact (Fig. 11) is of low amplitude and low duration. During the loading and unloading cycle, AE waveforms are of higher amplitude. In comparison to

Fig. 12 Typical comparison between power spectrum (FFT) of AE signal generated during the first stage of loading (plastic deformation), loading and unloading cycles of indentation test of alumina

the loading signal, the duration of the unloading signal is longer. This may be due to longer cracks or those which grow more slowly. In this example the frequency range of analysis is from 0 Hz to 1.0 MHz without any filtering. Therefore the lower-frequency components are considerable because of peripheral vibrations. The resonance frequency of the AE sensor (140 kHz), and the lower-frequency components (less than 200 kHz) repeat in all the FFT plots, thus we can neglect these parts of the spectrum and only discuss the higher-amplitude range. During the first plastic contact, almost no high-frequency component can be observed. With increasing load of indentation, first, the frequency components around 300 kHz with significant peaks appear and grow. At higher loads after saturation of the components around 300 kHz, the power of AE signals between 550 kHz up to 600 kHz also increases.

Considering previous studies⁽⁷⁾ and microscopic observation, it may be suggested that different frequency components, correspond to different stages of cracking. For example, lower frequencies might be related to median cracks or radial cracks, while during unloading, lateral cracks of higher-frequency components appear in the power spectrum. Thus, such

Fig. 13 A schematic summary of this study

a study can give different power spectrum patterns related to the kind of material and phase of cracking.

4. Discussion

4.1 Sources of acoustic emission energy

The results clearly show that release of elastic strain energy occurs with loads far below the fracture stress. The release of elastic energy could result from several sources, but in the present case, only two sources are likely: plastic deformation and crack phenomena. Particularly during unloading, lateral cracking is the main cause of acoustic emission.

The results of signal analysis confirm that the acoustical characteristics of the signals generated by the above sources, i.e., plastic deformation and cracking, are significantly different. With increasing cracking rate, the percentage of high-energy and high-oscillation events increases. The difference between the released energy levels depending on the sources can be predicted theoretically; however, the basis of calculation is different. The work rate of plastic deformation $\dot{W}$ is the energy source of AE when plastic deformation occurs in ceramic material, and is given by⁽⁸⁾

$$\dot{W} = \sigma' \dot{\epsilon} V \quad (1)$$

when the material is subjected to a constant stress (σ) and strain rate ($\dot{\epsilon}$). V is the volume of deformed material and σ' is the stress deviator.

On the other hand, assuming the velocity of crack propagation in ceramic to be constant, the energy rate of AE during crack growth, $\dot{U}$, can be presented as⁽⁹⁾

$$\dot{U} = \eta \sigma^2 c / E, \quad (2)$$

where

σ = applied stress

c = crack length

E = elasticity modulus

η = proportionality constant.

In the case of ceramics in which plastic deformation is much less than crack propagation, the rate of strain energy released by plastic deformation, Eq. (1), is less than the energy released by cracking, Eq. (2). Reasonably, we can predict greater generation of AE energy in the brittle mode than in the ductile mode during the machining process of fine ceramics.

4.2 Cracking nucleation threshold

The prediction of the threshold load in which the material changes from plastic deformation to cracking is quite important for a successful interpretation of AE signal analysis. In general, for ceramic materials which are not transparent, it is very difficult to determine the threshold load. Thus different theoretical estimations have been suggested^{(10),(11)}. For the ceramic material used in this study, using Lawn and Evan's theory⁽¹¹⁾, the critical load is about 2 N at which the first median cracks form, and all the signals emitted below this level are assumed to be related to plastic deformation. However, according to Perrott's⁽¹⁰⁾, Lankford and Davidson's⁽¹⁾ and Cook and Pharr's⁽⁴⁾ theories and observations under belief that threshold cracking is related to radial rather than median cracking, a load of about 0.4 N can generate primary radial cracks in this ceramic. To gain sufficient confidence in the dependence of AE signals on plastic deformation, the smaller amount, i.e., 0.4 N, was selected as the threshold load, even though the radial cracks were not observed on the surface up to 10 N indentation load.

5. Conclusions

Indentation of alumina was carried out with the goal of evaluating the deformation mode and cracking by means of acoustic emission. Figure 13 schematically shows the conclusions. A summary of the results is as follows.

(1) Increasing the indentation load increases the surface cracks as well as AE events. The rate of increase of AE events is similar to the rate of increase of indentation load. Unit indentation load generates more cracks when it is applied at higher loading rate.

(2) Surface cracks of ceramics are characterized by high-amplitude, long-duration, and high oscillation AE events.

(3) AE signals from plastic deformation are of low frequency. During cracking, signals of frequency around 300 kHz and between 550 and 600 kHz were detected.

(4) Because of the low level of noise in indentation tests, this method is very effective to study AE

characteristics of the plastic deformation and fracture of fine ceramics during machining.

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