Evaluation of crack growth stage of sapphire under scratching based on AE signals

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Abstract. For hard-brittle materials, crack initiation and growth is an important factor to determine the surface quality of components during machining process. In this paper, the crack growth stage of sapphire was investigated based on acoustic emission (AE) signals through single-grit scratch experiments. The AE waveform indexes, i.e. fractal and frequency characteristics, were fully analyzed and correlated with groove microstructure of specimen after tests. The research shows that the specimen undergo four stages of crack growth successively as scratch depth increasing. It is found that the fractal dimension (FD) and frequency characteristics of AE signals are distinctive to various damage behaviors and be used to evaluate crack growth stage induced in machining process effectively. Especially, the FD distribution is sensitive to the occurrences of the critical damages and removal modes resulting from crack growth in scratch procedure. This paper can shed light on the control of surface integrity and subsurface damage of hard-brittle materials in ultra-precision manufacturing.

1. Introduction
Sapphire (α-Al₂O₃) is a promising ceramic material which has excellent optical performance and superior mechanical, thermal, chemical properties and has been widely used in optics, electronics, medicine and military fields [1–4]. The damage-free surface/subsurface of workpieces are required to achieve their working performance. However, it is significantly difficult to obtain damage-free workpieces of sapphire due to its high hardness and brittleness. Therefore, the study on damage mechanisms and the evaluation of damage behaviors of sapphire are particularly important for achieving desirable workpieces.

It has been widely believed that the crack initiation and growth of workpieces during machining process are the fundamental cause of damages. Previous researches revealed that slip and twinning could provide crack nucleation under scratching and as loading proceeds, the cracks would grow sharply resulting in surface and subsurface damages. For damage behavior characteristic, acoustic emission (AE) technology has shown significant potential advantages as AE signals can be employed to distinguish different types of damage behaviors by capturing the process kinetics [7] and provide real-time information about damage evolution and modes. Wang et al [5,6] identified the anisotropic deformation and three material removal stages of sapphire during scratch tests using AE signals in frequency domain. Tymiak et al [7] conducted monitoring nano-indentation with an AE sensor integrated into an indenter tip and provided two types of AE signal pattern associated with the initial stages of plasticity. However, there is few researches on the evaluation and characterization of crack growth of sapphire via AE technology so far. Therefore, it is necessary to carry out related research and exploration in crack growth evaluation from AE aspects.
Encouragingly, AE technology has also been widely applied for the plastic and brittle damage characterization of other ceramics, including alumina [8,9], silicon carbide [10,11], single crystal silicon [12] and ceramic matrix composites[13]. In these researches, AE parameters, such as AE counts, cumulative AE energy, cumulative AE hits, AE energy distribution, etc., are broadly utilized to characterize damage behaviors. It should be noted that those parameters are strongly dependent on the threshold and other settings in AE data acquisition system, which are decided by researchers and experimental procedure [14]. For instance, the number of AE counts varies according to the change of pre-set threshold. Besides, apart from the strain-energy released within a material, the intensity of cumulative AE energy in recorded AE data is dependent on sample geometry, material, and coupling agent. Therefore, it is challenging to distinguish the damage evolution accurately using these AE parameters considering the variations of researchers’ experience and experimental conditions. In contrast, the waveform of AE signals, e.g., fractal feature, frequency spectrum, etc., are more independent parameters.

The fractal theory was first introduced by Mandelbrot in the 1970s to characterize the scale invariance characteristics of irregular objects based on self-similarity [15,16]. Recently, it has been proved to be promising in characterizing some complex graphics and processes in science. In fractal analysis, the fractal dimension (FD) is a quantitative parameter to show fractal features. Moreover, FD was widely adopted for AE analysis in many studies [15–20], especially in building and mining engineering [15,17,19,20]. In addition, the frequency components of AE data were also discussed for damage identification widely and some critical damages have been characterized by the bandwidth and intensity of frequency components [21–23]. In this paper, the FD and frequency components of AE waveforms produced in scratching process was investigated to evaluate crack growth degree of sapphire.

This paper aims to investigate the evaluation of crack growth of sapphire via AE technology in single-grit scratch tests. The fractal and frequency characteristics of AE waveforms recorded in scratching process were mainly studied. This study is conducive to elucidating the brittle damage evolution of sapphire and contributes to the development of damage-free machining technology. Moreover, the proposed AE parameters in this paper are not limited to sapphire, but can be applied to other hard-brittle materials as well.

2. Materials and methodology

2.1. Materials and Experimental setup

The C-plane sapphire sample, with 22 mm diameter and 3 mm thickness, was employed in single-grit scratch tests along [0110] direction. Before experiments, the sample was polished to remove original subsurface/surface defects with surface roughness Ra less than 0.2 nm. The Vickers indenter was utilized and the diagonal line of Vickers indenter was parallel to the [0110] direction in experiments. In this study, the scratch testing was conducted on an ultra-precision machine. As shown in Fig. 1, the sample surface was mounted on a 1/2000 slope wedge by heat softened glue, thus a ramp scratch depth increased linearily from 0 to 1 µm along a 2 mm scratch length. The scratching speed was 1.5 mm/s in this work. The AE sensor was mounted under the sample with a sampling frequency of 2 MHz. To reduce the attenuation of the AE source signals, the receiving surface of the AE sensor contacted with the sample surface directly, and a coupling agent (vacuum grease) was applied between the contact surfaces.
2.2 AE parameter analysis

2.2.1 Fractal dimension. Many methods of calculating fractal dimension (FD) have been proposed, including Hausdorff dimension method, box dimension method, capacity dimension method, correlation dimension method, etc. [34]. Among them, the box dimension method is more reasonable and is commonly adopted by other researchers [25,35]. Thus, the box dimension method was used to calculate the FD in this paper.

It was assumed that the recorded AE data was the vector $X_{AE} = \{x_1, x_2, \cdots, x_n\}$, and the number of a square box with sides $r$ to cover data $X_{AE}$ was $N_r(X_{AE})$. In general, when $r \to 0$, the relationship between $N_r(X_{AE})$ and $r$ can be expressed in Eq. (1):

$$N_r(X_{AE}) \propto r^d$$

(1)

where the vector length $n$ was 10000, $d$ was the box dimension.

The box dimension $d$, i.e. fractal dimension, could be calculated using Eq. (2)

$$d = -\lim_{r \to 0} \frac{\log N_r(X_{AE})}{\log r}$$

(2)

2.2.2 Frequency characteristics. In this work, the frequency characteristics of recorded AE signals during scratching process were investigated. The parameters of time-frequency spectrum (TFS) and peak frequency (PF) of the spectrum were analyzed.

In frequency analysis, each 10,000 data of raw AE signals were processed by Fast Fourier Transform (FFT) to obtain the frequency-domain characteristics.

3. Results and discussions

3.1 AE features during scratching process

The AE features are correlated with damage behaviors during scratching process. Fig. 2 shows the variation of AE signal amplitude as scratching depth increasing from 0 to 1.1 $\mu$m. It can be seen that the amplitude of AE signals increases continually but not steadily, and burst signals, generated by brittle fracture, appear with the occurrence of brittle damage as scratching depth (SD) increases. The microstructures of scratched groove were illuminated in Fig.3. When SD is small enough there is no crack appeared. As SD increases gradually, lateral cracks emerge firstly on specimen subsurface, then
radial cracks emerge on surface subsequently. Further increasing SD the lateral and radial cracks are grew consequently and subsurface/surface are damaged further by cracks propagation. When the propagation of lateral cracks and radial cracks are interfered with each other the material is removed by spalling. It means that the crack growth results in the variation of removal mode from ductile to brittle and destroyed surface integrity is occurred. When SD increases continually the crack growth becomes more serious and surface integrity are worse. As shown in Fig.2, the burst signals are changed from minor to intense gradually during crack growing. Such it indicates that the degree of crack growth can be characterized by the intensity of burst signals qualitatively.

![Fig. 2. As recorded AE signals during scratching process.](image)

![Fig. 3. Damage evolution of scratched groove during scratching process.](image)

3.2 Fractal characteristics of AE signals

The brittle damage behaviors, i.e. crack growth progress, during scratching process was discussed with the aid of AE technology in this section. The fractal dimension (FD) of AE signals was obtained based on the calculation method described in Section 2.2.1, and the variation of FD data with scratching depth is plotted in Fig.4. It is observed that as scratching depth increases, the FD values decrease and become more dispersed. Moreover, it is worth noting that the FD values distribute in three domains regarding data values during the entire damage evolution. When the scratching depth ranges from 0 to 270 nm the first-data-domain appears, as shown by the red dots in Fig. 6. In this domain, the FD values vary slightly, from 1.72 to 1.62, with minor fluctuation. As the scratching depth exceeded 270 nm, the second-data-domain is initiated, with FD values ranging from 1.61 to 1.46 (SD: from 270 to 1100 nm), as shown by the blue square in Fig.4. It can be seen that the data dispersity are enlarged and data values are smaller in the second domain. Once the scratching depth exceeds 375 nm, the third-data-domain emerged, as shown by the green rhombus in Fig.4. In this domain, the data values range from 1.49 to 1.32 (SD: from 375 to 1100 nm) with larger data dispersity and data range than the first two, as shown in Fig.5.
Importantly, the above three domains are related on different crack growth stages during scratching process, as discussed below. In order to reveal the influence factor of FD distribution, the corresponding microstructures of groove during scratching process were analyzed. The Fig. 6 shows the relationship between FD distribution domain and crack growth stage. It suggests that the crack growth progress of sapphire during scratching can be divided into four stages, i.e. lateral and radial cracks emergence (Stage I), radial crack shallow than lateral crack (Stage II), radial crack depth deeper than lateral crack (Stage III) and lateral crack propagated to specimen surface (Stage IV). As shown in Fig. 6, it should be noted that as scratching depth increases the crack growth can change the interactions among cracks, specimen surface and groove boundary, determining different damage behaviors. From Stage II to Stage IV, the interaction is superposition of lateral and radial cracks, intersection of lateral and radial cracks and interception of the lateral crack by radial crack, specimen surface and groove boundary, respectively, as illustrated in Fig. 6. In addition, when crack growth is evolved from Stage III to Stage IV, the removal mode is transformed from ductile to brittle, and the surface integrity becomes deteriorated. Note that the brittle-ductile transition (DBT), attributed to the tears on groove walls, is occurred in Stage IV. It indicates that tears in DBT and spalling in brittle removal mode resulted from crack serious growth can lead to the third-domain of FD distribution of AE signals.

**Fig. 4.** FD distribution of AE signals during scratching process.

**Fig. 5.** Discrete coefficient of FD and the sketch map of crack growth at different stages.
Fig. 6. The layers of FD data domain and the corresponding crack growth stages.

Therefore, the crack growth degree (from Stage I to Stage IV) can be evaluated by the domains of FD distribution, i.e. when FD data are distributed only at the first-domain the crack growth are stayed at Stage I; when FD data are distributed at the first-and second-domains the cracks are grew to Stage II and Stage III; when FD data are distributed at the three domains the cracks are grew to Stage IV.

3.3 Frequency characteristics of AE signals

Fig. 7 presents the time-frequency spectrum (TFS) of AE signals against scratching depth during scratching process. As shown in Fig. 7, six frequency bands are appeared, i.e. 14.4–40.4 KHz, 47.6–80 KHz, 86.8–161.4 KHz, 167.6–202.6 KHz, 233.8–289.2 KHz and 356–369.4 KHz respectively. The frequency band of 356–369.4 KHz is initiated when cracks are grew to Stage IV. In addition, the energy in each frequency band increases as scratching depth increases, especially in Stage IV. Thus, it is concluded that much larger energy of AE signals could be generated in Stage IV than that in other crack growth stages. Besides, it should be noted that there is distinct discrimination in frequency spectrum when Stage I and Stage IV are initiated, as shown by the arrows in Fig. 7. In addition, as shown in Fig. 7, the frequency range is changed from 14.4–289.2 KHz to 14.4–369.8 KHz when spalling behavior is initiated.
Fig. 7. Time-frequency spectrum of AE signals: (a) the three dimensional image, (b) the contour map; where f1–f6 are values of frequency band, i.e. 14.4–40.4 KHz, 47.6–80 KHz, 86.8–161.4 KHz, 167.6–202.6 KHz, 233.8–289.2 KHz and 356–369.4 KHz respectively.

The trend of peak frequency (PF) numbers during damage evolution is presented in Fig. 8. It is noteworthy that some intermittent PFs emerge after the initiation of radial cracks during crack growth progress. The intermittent PFs increase progressively as cracks grow, especially after the occurrence of Stage IV. These intermittent PFs are related to specific cracks interactions, giving these actions, e.g., radial crack emergence, superposition and intersection of lateral and radial cracks, and spalling behavior resulted from the interception of lateral crack by radial crack, specimen surface and groove boundary, etc. are occurred intermittently as well. Thus, the intermittence of PF is an effective indicator for crack growth stage during scratch process.

Fig. 8. The trend of PF numbers during scratching process.

4. Conclusions
In this paper, the evaluation of crack growth in sapphire scratching process was studied by AE technology. The fractal and frequency characteristics of AE signals were discussed. Specifically, the FD distribution of AE signals in scratch can be classified to three domains which are corresponded to different crack growth stages, i.e. when FD data are distributed only at the first-domain the crack growth are stayed at Stage I; when FD data are distributed at the first-and second-domains the cracks are grew to Stage II and Stage III; when FD data are distributed at the three domains the cracks are grew to Stage IV. As the cracks at Stage IV could lead to material spalling, the third-domain of FD distribution is an indicator for material removal mode transform from ductile to brittle. In addition, when cracks are initiated and propagated severely, corresponding to Stage I and Stage IV, there are distinct features in Time-Frequency spectrum. Six frequency bands are appeared, i.e. 14.4–40.4 KHz, 47.6–80 KHz, 86.8–161.4 KHz, 167.6–202.6 KHz, 233.8–289.2 KHz and 356–369.4 KHz respectively. The frequency band of 356–369.4 KHz is initiated when cracks are grew to Stage IV. Besides, the intermittent PFs emerge
after the initiation of radial crack. The intermittent PFs increase progressively as cracks grow and can characterize different crack growth stages during scratch process. This work shows that the crack growth stages during scratching could be evaluated effectively via AE data.

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