The wear detection of mill-grinding tool based on acoustic emission sensor

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Abstract
The monitoring of tool wear plays an important role in improving the processing efficiency and reducing the production cost of enterprises. This paper is focused on the detection of electroplated diamond mill-grinding tools by using the acoustic emission sensor. The wear stages of mill-grinding tools are divided into three parts, namely initial wear stage, normal wear stage, and severe wear stage. The characteristic parameter method and the waveform analysis method are applied to analyze the acoustic emission signals. The wear characteristics of the tool and workpiece in different wear stages are observed and analyzed. The results indicate that the acoustic emission waveform is relatively stable in the initial wear stage, and the continuous acoustic emission signal is dominated. Moreover, the diamond abrasive grains are mainly worn and slightly broken in the normal wear stage, and there are some pits on the machined workpiece surface after the initial wear stage. In the severe wear stage, most of the abrasive grains are broken or broken in a large area, and there are burst acoustic emission signals in the waveform.

Keywords Wear detection · Zirconia ceramic · Mill-grinding tool · Acoustic emission

1 Introduction
In recent years, acoustic emission technology, as a mature non-destructive testing method, has been more and more widely used in many fields, such as various industries in national defense and the economy [1]. With the continuous improvement of acoustic emission technology, it has also been applied in the field of mechanical structures [2, 3], component crack, leakage [4], and tool wear detection [5].

In the aspect of mechanical equipment operating condition and fault diagnosis identification, Faris et al. [6] explored the characteristics of acoustic emission and vibration signals in diagnosing a bearing defect in the planetary gearbox. What’s more, the application of acoustic emission testing technology to fatigue and crack detection of components can effectively predict other types of faults such as crack initiation and propagation [7]. In the field of machining, metal burn is a common problem. Different degrees of metal burns will cause different degrees of damage to related components. Gao et al. [8] used an infrared thermal imager and acoustic emission sensor to explore the relationship between the combustion degree of 1045 steel and acoustic emission signal, which provided guidance for metal combustion detection.

As for the process of mechanical processing, in addition to metal burns, tool wear also plays a very important role in the control of machining quality [9]. Therefore, the subject of machining tool wear has become a research focus of many scholars. Liang et al. [10] conducted a tool wear experiment on dry cutting titanium alloy Ti-6Al-4 V, and observed the tool wear characteristics, and analyzed the tool wear mechanism. However, many scholars directly explore the wear of tools through the wear experiments of machining tools, such as end-face milling [11], drilling [12, 13], turning [14], grinding [15], and other tool wear experiments. Combined with the wear conditions of tools, the wear mechanism of machining tools is analyzed. Through sawing experiments, Zhou et al. [16] comprehensively analyzed and compared the wear characteristics of multi-blade combination saw with different diameters in the process of processing granite combined with the load model, the blade height of diamond grains, and the wear morphology of metal substrate.
Many scholars have explored the wear mechanism of the tools [17]. However, the deformation of the workpiece, chip formation, and the friction between the tool and the workpiece surface are closely related to the force signal in the machining process [18]. Therefore, many scholars have further used the force sensor to monitor the wear of the tool while studying the mechanism [19, 20]. Tool wear will cause certain mechanical vibrations, so the acceleration sensor can also be used to monitor the tool wear. Wafaa et al. [21] applied a three-dimensional acceleration sensor to collect the vibration signal of turning process, and the average power of the vibration signal was used as the characteristic value to judge the tool wear state. As a modern non-destructive testing technology, acoustic emission monitoring technology started from a German researcher of Kaiser in the 1950s, and it was gradually introduced into the field of mechanical processing by scholars [22]. The acoustic emission detection technology has been applied in some metal or composite materials, and it has gradually been widely used in the fields of tool wear detection [23–25]. Gomez et al. [26] studied and found the relationships between acoustic emission (AE) mean power and different degrees of wear in twist drill bits during the drilling process. To obtain the tool breakages, Sun et al. [27] analyzed the components of acoustic emission data and screen the corresponding feature samples. At present, few scholars, however, are studying the wear monitoring of diamond mill-grinding tools. In addition, the acoustic emission sensor has strong adaptability and is not affected by the vibration of machine tools. Therefore, this paper selects the acoustic emission sensor to monitor the wear state of tools for mill-grinding zirconia ceramics.

The acoustic emission signal waveform characteristics of diamond mill-grinding tools in different wear conditions are analyzed and compared, and the eigenvalues used to characterize different wear stages are extracted. The wear characteristics of mill-grinding tools in different wear stages are tracked and the morphology of workpiece are observed and described in detail, and the influence of mill-grinding tool wear on acoustic emission signal and workpiece surface quality is analyzed.

2 Experimental setup

2.1 Material and equipment

The electroplated diamond mill-grinding tools produced by Shenzhen Changxing Technology Co. LTD are used in the experiment. The grain size of diamond is 120#, and the mean grain size of diamond abrasive grains is about 106–120 μm. The diameter of the mill-grinding tool is 10 mm. In this experiment, the workpiece material is zirconia ceramic with the size of 150 × 80 × 10 mm, which is widely used in 5G high-end ceramic mobile phone backplane. The reason is that the backplane made of zirconia ceramic has many excellent features such as no signal interference and good wear resistance [28]. However, the zirconia ceramics have high material hardness and high brittleness. The properties of zirconia are listed in Table 1.

| Properties          | Unit | Value   |
|---------------------|------|---------|
| Density             | g/cm³| 6.05    |
| Vickers hardness    | HV₀.₅| 1175    |
| Poisson’s ratio     | /    | 0.22–0.23|
| Elasticity modulus  | GPa  | 200     |
| Fracture toughness  | Mpa m¹/²| 8.0    |
The signal input end of the universal 2/4/6 preamplifier is connected with the acoustic emission sensor. The signal received from the sensor is amplified, and then transmitted to the PCI-2 acoustic emission acquisition card through the cable. The acquisition card inserts into the corresponding card slot reserved in the acoustic emission chassis of Micro-II produced by Physical Acoustics Corporation (PAC). The original signal data is saved through the AEwin software, and the signal can be displayed on the screen in real time. At the same time, the original acoustic emission signal can also be exported offline for post-processing. The specific parameters of the acoustic emission sensor are shown in Table 2. To ensure the accuracy of AE acquisition, a pencil lead-breaking experiment was carried out before the mill-grinding process. And the coupling of the acoustic emission sensor and the influence of environmental noise on the signal acquisition were determined through the experiment. According to the results of the lead-breaking procedure, the threshold value of the acoustic emission signal was set to 60 dB. The amplification factor is 20 dB. The sampling rate of the acoustic emission signal is 1 MHz.

### 2.3 Experimental procedure

The wear platform of mill-grinding tool was built in the MORI DMU 50 5-axis machining center, and the diamond tool wear experiments were conducted on the platform. The acoustic emission monitoring system was used to collect the mill-grinding process signal for the full cycle of the tool life. Specifically, the zirconia ceramic workpiece was glued to the pre-designed fixture with paraffin wax, and the ceramic workpiece was pre-ground with diamond wheel to ensure its flatness preliminarily. Then, it was clamped by the general fixture. By using a dial indicator and combined with the adjustment function of the five-axis rotation around the y-axis, the leveling work was accomplished, so that the flatness range of the zirconia ceramics processed by each mill-grinding process is within 5 μm. Then, the rotating cutting force dynamometer (RCD, 9170A) of Kistler and the acoustic emission system were installed and debugged to record the force signals and acoustic emission signals of mill-grinding in real time. The force measuring system is mainly used to assist tool setting and preliminarily judge the wear state of diamond tools in the mill-grinding process. The specific test platform is shown in Fig. 1.

According to the actual production parameters of the enterprise, combined with the actual test conditions, the fixed mill-grinding machining parameters: the spindle speed (S) is 8000 rpm rotating speed, the depth of mill-grinding process (ap) is 15 μm, and the feed speed (v) is 200 mm/ min. The whole wear experiment of mill-grinding processing did not use cutting fluid. In order to further observe the wear of diamond mill-grinding tools, the ultra-depth-of-field electron microscope of KEYENCE VHX-1000 was used to track and monitor the wear stages of mill-grinding tools. For the surface morphology of zirconia ceramic workpieces in different wear stages, the optical 3D profilometer (Zygo NewView 7300) and the desktop tungsten filament scanning electron microscope (JEOL JSM-IT500) were used for observations respectively.

### 3 Results and discussion

Different wear stages of the acoustic emission signals as well as the mill-grinding tools and zirconia ceramic workpieces have been analyzed separately. In general, the processing and analysis methods of acoustic emission signal mainly include the characteristic parameter method and the waveform analysis method [18]. In order to analyze and compare the main characteristics of different wear stages, this section mainly uses the amplitude characteristic parameters of the acoustic emission signal in the mill-grinding process. For the waveform of acoustic emission signal, the fast Fourier transform (FFT) method [29, 30] and time–frequency domain wavelet packet analysis method [31] are used to analyze the acoustic emission signal of different wear stages in the mill-grinding process. Furthermore, the wear characteristics and mechanism of the diamond mill-grinding tools in different wear stages and their effect on the zirconia ceramic workpieces have also been analyzed. The results will be discussed in each section.

### 3.1 The analysis of sensor signals

The research on force signals is relatively mature at present, and its validity has been verified. Therefore, the dynamometer was selected as the index sensor to provide convenience for the preliminary construction of monitoring the mill-grinding tool wear state. According to the characteristics of mill-grinding force signals in different wear stages and the diamond abrasive wear of mill-grinding tools, the wear stages of diamond tools in this paper are divided into three parts, namely initial wear stage, normal wear stage, and severe wear stage. The acoustic emission waveform is
relatively stable in the initial wear stage, and the continuous acoustic emission signal is dominated. In normal wear stage, the amplitude of the acoustic emission signal gradually increases in the stable processing area, whereas there are burst acoustic emission signals in the waveform, and most of the abrasive grains are broken or broken in a large area in the severe wear stage. In this section, the further analysis of the acoustic emission signals in different wear stages is carried out.

The characteristic parameter of acoustic emission signal amplitude refers to the maximum amplitude of acoustic emission signal waveform during each impact. Theoretically, when the acoustic emission sensor output 1 μV is defined as 0 dB, the amplitude of original signal collected by the acoustic emission system is $V_{AE}$ (unit: μV), and the conversion formula for the amplitude of the acoustic emission signal $dBAE$ is as follows:

$$dBAE = 20 \log \left( \frac{V_{AE}}{1 \mu V} \right)$$

In the process of mill-grinding, the duration of 1.024 s is taken as the impact point of acoustic emission signal in different wear stages, and the distribution of its amplitude over time is shown in Fig. 2. The approximate range of cut in and cut out areas can be judged, as shown in the dotted box in the figure above. The stable stage of mill-grinding at different wear stages is mainly between 15 and 33 s. In the initial wear stage, the acoustic emission signal of mill-grinding process shows a relatively stable state, and its amplitude is about 95–100 dB. While in the normal wear stage, its amplitude distribution is more scattered than that in the initial wear stage, and its average amplitude is around 100–105 dB. In this stage, the amplitude of local impact point fluctuates. The reason is that some diamond grains on the mill-grinding tool are broken, and the new mill-grinding edges will gradually appear, resulting in a smaller acoustic emission amplitude of the partial impact point. At the same time, most of the diamond abrasive grains gradually wear with the accumulation.
of mill-grinding distance, so the amplitude increases to a certain extent compared with the initial wear stage. In the severe wear stage, the distribution of acoustic emission signal amplitude is 108–112 dB or so, and the position on the scatter graph is higher than that of the normal wear stage and the initial wear stage.

In order to further analyze and extract the waveform characteristics of acoustic emission signals in mill-grinding process under different wear conditions, the acoustic emission waveform signals of initial wear stage, normal wear stage, and severe wear stage are selected for processing respective. Because the generation rate of the acoustic emission signal is changeable, some scholars divide the acoustic emission signal into burst type and continuous type [32].

The time domain waveforms of acoustic emission signals in different wear stages are shown in Fig. 3. Under the experimental conditions described in this paper, the acoustic emission signals of diamond tool in the initial wear stage can be regarded as continuous acoustic emission signals. With the continuous wear of diamond grains, the burst type acoustic emission signals appear in the normal wear stage, and the probability of burst type acoustic emission signal increases in the severe wear stages.

It can be seen from the time-domain waveform that the voltage value of the acoustic emission time-domain signal increases to a certain extent with the continuous wear of the mill-grinding tool. The acoustic emission signals of mill-grinding process in different wear stages are analyzed, and the frequency domain diagrams are obtained by using fast Fourier transform respectively [33], as shown in Fig. 4.

According to the frequency spectrum comparison of acoustic emission signals in different wear stages above, it can be seen that the amplitude of the acoustic emission signal spectrum gradually increases with the continuous wear of the electroplated diamond mill-grinding tools in the low-frequency band region of 0–125 kHz. Nevertheless, in the region of 125 k–250 kHz, the amplitude of the frequency

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**Fig. 3** Time domain waveform of acoustic emission signal in different wear stages

**Fig. 4** Frequency spectrum comparison of acoustic emission signal in different wear stages
domain decreases with the increase of wear degree of diamond tools. When the frequency range is greater than 250 kHz, the average amplitude of the acoustic emission signal in the initial wear stage is reduced to a certain extent compared with the other two stages.

As for the analysis results of the time domain and frequency domain, it can be obtained that the burst type and continuous type acoustic emission signals in the mill-grinding process are concentrated in different frequency bands. To further confirm the specific distribution of the burst type and continuous type acoustic emission signals in the time domain and frequency domain, it is necessary to analyze the original signal. Furthermore, the frequency domain segment of acoustic emission signal is analyzed, so the time–frequency domain analysis tool is selected to decompose the acoustic emission signals in different wear stages during the mill-grinding process. Although the traditional discrete wavelet transform provides flexible time–frequency resolution, it has a lower resolution in the high-frequency region. Therefore, the acoustic emission signal is analyzed by wavelet packet transform (WPT) in this paper [34].

By comparing the characteristics of different wavelet basis functions, the acoustic emission signals of different wear stages in the mill-grinding process are decomposed into three layers by using the fourth-order Daubechies (db4) wavelet basis functions respectively. Then, the signals of each stage are evenly divided into eight frequency bands. And the signal length of each frequency band is 1/8 of the original signal. Finally, the wavelet packet reconstruction is carried out for each frequency band after decomposition, and the amplitude spectrum and the energy ratio of each frequency band are calculated. The comparison chart of wavelet packet energy ratio in each frequency band is shown in Fig. 5.

For the different wear stages of diamond mill-grinding tools, the acoustic emission signals energy ratio of each reconstructed frequency band is shown in Table 3. In general, the percentage of wavelet packet energy in the frequency band of 0–125 kHz exhibited an upward trend, while that of the remainder frequency band remained in decline. To start with a frequency band of 0–125 kHz, the proportion of energy increased dramatically with the deterioration of diamond tools, from an approximate 18.73% in the stage of initial wear to an all-time high of 70.59% in the severe wear stage, which brought about a 3.77-fold growth. Therefore, this frequency band could be well used to determine the state of tool wear.

By contrast, an over 40% rise was recorded regarding the 125–250 kHz frequency band, reaching about 22.93% in the third wear stage, compared to 39.45% in the first wear stage. When it comes to the 750–875 kHz frequency band, the energy ratio of the acoustic emission signal in the three wear stages is 3.22%, 0.40%, and 0.19%, respectively, and the energy ratio in the initial wear stage is 8.05 times higher than that in the normal wear stage. Similarly, albeit at a different lower rate, the decline in the remaining frequency bands, the proportion of energy presents a certain downward trend with the constant wear of mill-grinding tools. Also noteworthy is that the acoustic emission signals energy proportion in 275–500 kHz of the severe wear stage came in the third position, with above 5%, compared to merely less than 1% of the other frequency bands from 250 to 1000 kHz.

### Table 3 The percentage of wavelet packet energy in each frequency band

| Frequency range/kHz | Initial wear stage/% | Normal wear stage/% | Severe wear stage/% |
|---------------------|----------------------|---------------------|---------------------|
| 0–125               | 18.73006             | 50.85412            | 70.58783            |
| 125–250             | 39.44957             | 36.18317            | 22.93493            |
| 250–275             | 2.44126              | 0.64694             | 0.35606             |
| 275–500             | 32.69444             | 11.3438             | 5.64838             |
| 500–625             | 0.09263              | 0.00911             | 0.00515             |
| 625–750             | 0.66082              | 0.12017             | 0.06177             |
| 750–875             | 3.22077              | 0.39602             | 0.18764             |
| 875–1000            | 2.71045              | 0.44667             | 0.21825             |
The characteristics of mill-gridding tool and workpiece

With the increasing removal volume of zirconia ceramic materials, the number of wear diamond grains on the mill-grinding tool is gradually increasing in the selected area, and the wear degree of tool is also exacerbating, as shown in Fig. 6.

There is little difference of the grains in the selected area between the initial wear stage and the state without processing. This phenomenon is also consistent with the fact that the acoustic emission signal is relatively stable in the initial wear stage; in the normal wear stage, some of the diamond abrasive grains in the selected area are micro-fractured, and most of the diamond abrasive grains are mainly wear and tear; a worn belt is formed near the edge area of the diamond mill-grinding tool.
Fig. 7 Surface morphology of workpiece in different wear stages. a Before mill-grinding. b Initial wear stage. c Normal wear stage. d Severe wear stage.
in the severe wear stage. What’s more, most diamond abrasive grains in this area are fracture, broken in large areas, or semi-broken. The wear zone is mainly due to the fact that the undischarged zirconia ceramic powder is attached to the diamond abrasive grains during the process. With the decrease of the height for the diamond grains, there is a relative movement between the ceramic powder and the electroplating layer of the mill-grinding tool in this process. The friction between them aggravates the wear of the diamond mill-grinding tools, which makes most of the diamond grains passivated or even invalid.

So as to verify its wear state, the zirconia ceramic workpieces processed in different wear stages were selected in this paper. The surface morphology before and after mill-grinding process was detected by the optical 3D profilometer and scanning electron microscope, as shown in Fig. 7.

In the initial wear stage, some of the diamond grain protrusion height is comparatively high. Therefore, these diamond grains participate in the processing under a fixed cutting depth, leaving regular scratches on the surface of the processed zirconia ceramic workpiece, and the phenomenon of plastic side flow can be seen in the microstructure. The height data on the scratches were extracted by using the optical 3D profilometer, there are about 11 wave peaks, and the length of the sample is 0.283 mm in Fig. 7a; therefore, the difference between adjacent wave peaks is about 0.026 mm, which is almost equal to the feed per revolution of the spindle \( d_s = 200/8000 = 0.025 \text{mm/r} \). As shown in Fig. 7b and c, there are pits on the surface of the processed workpiece in the normal wear stage and the severe wear stage. In terms of the normal wear stage, the plastic side flow of the zirconia ceramics is slipped, accumulated, and fractured, which is also coincided with the burst type of the acoustic emission signal. What’s more, in the severe wear stage, there is a scaly-like uniform crack formation in the deep part of the pit. This is because the diamond grains involved in the processing have been blunt in this wear stage, and their processing ability has decreased, thus affecting the quality of the machined surface.

4 Conclusion

This paper presents an experimental study on the tool wear in mill-grinding of zirconia ceramic with the electroplated diamond mill-grinding tool. In the mill-grinding process, the variation of acoustic emission characteristic parameters and acoustic emission waveform characteristics in different wear stages are analyzed. Furthermore, an ultra-depth-of-field microscope is used to track and detect the mill-grinding tools. The desktop scanning electron microscope and the optical 3D profilometer are used to observe the surface morphology of the machined workpiece. And the effect of the tool wear is analyzed as well. Main conclusions from the performed research could be drawn as follows:

1. In the initial wear stage, the amplitude of the acoustic emission signal during the mill-grinding process is concentrated around 98.55 dB. And the waveform signal is relatively stable. At this stage, the distance between two adjacent scratches on the processed workpiece surface is about 0.0234 mm, which is almost consistent with the feed per revolution of the spindle. It can be seen from the morphology obtained by the scanning electron microscope that the phenomenon of plastic side flow appeared on the surface of the zirconia ceramic workpiece in this stage.

2. In the normal wear stage, the amplitude of the acoustic emission signal in the stable processing area is about 102.23 dB. Generally speaking, the distribution of the amplitude in this stage is more scattered than that in the initial wear stage. The abrasive grains on diamond mill-grinding tools are mainly wear and tear, and a small part of the grains are slightly broken. Compared with the initial wear stage, the surface quality of the processed workpiece has obvious scratches and pits, and the plastic side flow of zirconia ceramic is slipped, accumulated, and fractured, causing brittle fracture on the processed surface.

3. In the severe wear stage, the average amplitude of the acoustic emission signal is approximately 111.21 dB. Apart from that, the wavelet packet energy in the frequency band of 0–125 kHz showed a dramatic upward trend from initial wear stage to severe wear stage, while that of the other frequency band, such as 125–250 kHz, 275–500 kHz, etc. dropped substantially. Therefore, the change of the energy ratio of each different frequency band can be exploited to detect the wear state of the tool. Furthermore, the characteristic value would also be applied to establish an effective intelligent tool wear monitoring system. Meanwhile, the burst type acoustic emission signal occurred in the waveform in this stage, which is also corresponding to the fracture or failure of most abrasive grains on diamond mill-grinding tools. The reason is that the machining ability of the tool decreases with the dullness and failure of the diamond abrasive grains, which results in the scaly-like uniform crack formation in the deep part of the pit.

Author contribution The authors who contributed to this work have been listed in the author information. Wuzhen Huang: methodology, conceptualization, data curation, formal analysis, visualization, writing—original draft. Yuan Li: funding acquisition, investigation, methodology, project administration, resources, writing—review and editing. Xian Wu: investigation, validation, writing—review and editing. Jianyun Shen: conceptualization, supervision, investigation, resources.

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Declarations

Ethics approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate All of the authors have read and agree to publish the submit manuscript.

Consent for publication All of the authors have read and agree to publish the submit manuscript.

Conflict of interest The authors declare no competing interests.

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