Monitoring and analysis of ball milling process based on acoustic signal inversion

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Abstract. In order to understand the real-time material particle size inside the ball mill tank in the current actual ball mill process, the process for sampling and detection should be paused, which is very time-consuming and laborious. Through the real-time monitoring of the acoustic signals, the particle size of the materials in the tank can be indirectly detected according to the change of the acoustic signals so that the ball mill can be more efficient, energy-saving and convenient. In this paper, a method of collecting, analyzing and processing acoustic signals was designed by using acoustic signal collecting equipment and computer software in the process of ball grinding. The results show that the peak number of acoustic signal varies with the particle size of ball mill, and there is an obvious functional relationship between them. The ball milling process can be monitored and improved based on acoustic signal inversion.

1. Introduction

Many industries need the help of ball mill in the production process to complete the production tasks at present, such as metallurgy, mining, cement, refractory and other industries[1]. However, the energy consumption of ball mill is very huge in the actual production process. The electricity consumed by ore mill accounts for nearly 4% of the world's electricity consumption according to incomplete statistics. Moreover, ball mill is still an irreplaceable equipment in the future production for a long time. The reasons for high energy consumption in ball milling process are as follows: (1) the collision of internal grinding balls with materials is random, and energy will also be lost due to friction with materials besides crushing materials[1]; (2) After the powder reaches the critical minimum particle size, the particle size will not continue to change due to agglomeration[3]. As the particle size of the material cannot be known in real time, the ball milling will not be stopped in time after reaching the minimum particle size, which will also cause waste of resources. Therefore, studying the grinding process and using acoustic signal monitoring to detect the internal material particle size can effectively improve the grinding efficiency, save energy and protect the environment in the grinding process.

There are more and more examples of using machine hardware to solve problems with the progress of modern computer science and the rapid development of artificial intelligence technology, and acoustic monitoring technology is also developing rapidly. Acoustic recognition technology is gradually
attracting the attention of researchers and increasingly come into people's daily life in recent years. Its task is to study and use computers to extract acoustic signals and process these signals to realize human-computer interaction and intelligent control. Many examples of using acoustic signals can be seen everywhere in life, such as voice recognition, identity authentication, etc.. The use of acoustic signals in scientific researches touches many fields such as agriculture, biological identification, marine exploration, medicine, construction, machinery, artificial intelligence, etc. Charlie Mydlarz[4] and his team used low-cost acoustic monitoring devices to detect urban noise pollution and used microphones and mini PCs to form a network system to detect noise, which can capture, analyze and wirelessly transmit audio. Diego Llusia[5] et al. used acoustic detection to record biodiversity and increase the chance of discovering unknown species, so as to protect rare species and contribute to ecosystem research. Adam Glowacz[6] used acoustic signals to distinguish various electrical faults and mechanical faults of rotating electrical machines. Low-cost and easily available acoustic signals replace current signals with limited use. Minglu Li[7] and her team also tried to judge mechanical equipment faults by monitoring noise. And in the aspect of biological identification, William A. Searcy[8] discovered the refusal behavior of birds when they making sounds with acoustic signals.

However, there is still less research on the combination of the method of monitoring acoustic signals and ball milling process at present, so there is a large research space. The analysis of sound signals is also very important after the sound collection process is completed. Matlab can be used to help us to efficiently analyze and study the change law of acoustic signals as it has strong operation and processing ability for data and the programming process is relatively simple[9]. Therefore, Matlab is widely used in the analysis of acoustic signals at present. Guo Min[10] et al. analyzed the time-frequency of acoustic signals of stored grain pests, and proposed an effective and low-cost method for pest control based on Matlab. The acoustic signals collected in the ball milling process can also be analyzed and processed by Matlab, and the variation law of acoustic signals can be studied in combination with the change of material particle size and the change of friction force between grinding balls. Finally, a reasonable theory is put forward to explain the phenomenon.

Acoustic signals emitted in the ball milling process in more detail can be grasped through monitoring the ball milling process and easily analyze the changes of the energy of the ball milling movement, and then in the whole process, the change rule of the material particle size can be studied in combined with other automatic equipment. Controlling the ball milling process intelligently which greatly improves the convenience and practicability of the work can be realized, all of which provide new ideas and methods for future ball milling and have important research significance.

2. Experimental

Experimental Procedure. The calcined alumina powder was ball-milled by WZM 3-II experimental ball mill, while the radio microphone was fixed at the position near the tank body of the ball mill. The other end of the microphone was connected to a computer, in which audio processing software was used to collect sound waves throughout the whole process during ball-milling. The audio was imported into Matlab to analyze its characteristics after the collection was completed.

The mass of calcined alumina powder added was 1kg, and the mass of large, medium and small grinding balls was 2.7kg in total. Appropriate amount of grinding aid was added into the ball milling tank to accelerate the ball milling process at the same time of grinding. The ball mill was placed in an independent laboratory without other equipment during ball milling, and the ball milling experiment was selected to be carried out at night to minimize the interference of other noises. Sound waves were recorded and collected with audio processing software at a sampling frequency of 192000Hz at the beginning of ball milling.

It was known that the particle size of calcined alumina material will not change significantly after ball milling for 6 hours from previous ball milling experience. Therefore, sound waves would be collected for 8 hours for each ball milling to ensure that the whole process of sound signal change will be recorded.
Analysis Method of Sound Wave. Referring to the analysis method of audio frequency using Matlab software by Lu Ziwei et al.[11] and Li Jialiang[9], the amplitude and frequency of acoustic wave were analyzed. By using Matlab software, the WAV format audio signal file was first used as the input data to be analyzed[12], and the audio signal was analyzed and processed according to various functions provided in the software, such as time domain analysis, frequency domain analysis, digital filtering, signal synthesis, signal transformation, etc. The code of the time domain diagram and amplitude frequency diagram of the audio analyzed in this experiment was as follows:

\[
\begin{align*}
[x,fs]=\text{audioread('ex.wav',}[1024 5120]);
y=\text{fft}(x,N);
\text{magy}=\text{abs}(y);
\text{angley}=\text{angle}(y);
f=(0:length(y)-1)^*\text{fs}/\text{length}(y);
\text{subplot}(311);\text{plot}(x);\text{title('Time Domain Diagram')};
\text{subplot}(312);\text{plot}(f(1:N/2),\text{magy}(1:N/2));\text{title('Amplitude Frequency Diagram')};\text{grid}
\end{align*}
\]

As the audio files recorded by a processing software were 8 hours long and the WAV files were too large to be imported into Matlab for analysis, the 8-hour audio was intercepted every 30 minutes to analyze the change trend.

3. Results Analysis and Discussion.
The following Figure 1 (a-h) are respectively the amplitude-frequency diagram and phase-frequency diagram of different periods in a ball milling process analyzed by Matlab.

![Figure 1](attachment:figure_1.png)
Fig. 1 amplitude-frequency diagrams and phase-frequency diagrams of different periods

From the time domain diagram and amplitude frequency diagram of each time period, it can be seen as follows: (1) The frequency of acoustic signals are mostly concentrated in the same area with the increase of ball milling time, i.e. the frequency of sound emission does not change significantly; (2) The time domain diagram of each time period has obvious changes as time goes on, showing more peaks and troughs and more peaks with larger amplitude in the same time period.

The fluidity of powder can reflect the technological properties of powder, such as the storage, transportation, packaging and other processes. What the fluidity of powder generally includes are as follows: angle of repose, plate angle, compressibility, homogeneity, agglutination, etc. However, the fluidity of the powder will also change with the change of the particle size of the powder. The fluidity may deteriorate with the decrease of the particle size as the particle size decreases, and may also improve with it. This is related to many factors such as the grinding system of the materials, the nature of the particles themselves, and the range of particle size distribution.
It is speculated that the above waveform change phenomenon is due to the fluidity change caused by the change of alumina particle size, and the friction between the ball milling medium and the material also changes. The specific manifestations are as follows: when the particle size of the material is large in the early stage of ball milling, the friction force between the ball and the material is large, and most of the energy of the ball is consumed by friction with the material during the ball motion, so the chance of hitting the wall of the ball milling tank is small, and the speed is small, so the number of peaks and the amplitude is small. With the passage of time and the particle size of the material gradually decreases, the friction between the grinding balls and the material decreases\(^{[15]}\), so the grinding balls have more chances to impact the tank wall of the ball milling tank, and the impact speed also increases, so the amplitude increases and the number of wave peaks increases\(^{[16]}\).

The repose angles of the materials before, during and after ball milling are measured to be 50°, 65° and 70°, respectively, so the fluidity of the alumina grinding used in this test becomes worse as the particle size decreases. The smaller the particle size is, the worse the fluidity between materials is, but the friction between materials and grinding balls is reduced. This can be verified by the following experiments.

Taking three beakers of the same size and filling them with the materials before, during and after ball milling. Dropping the three grinding balls of the same size freely at the same height above the beakers, and observe the depth at which the three grinding balls fall into the powder. The result is deepening in turn. This shows that the friction force decreases when the ball moves in the later stage of ball milling, i.e. in materials with smaller particle size. The reason for the friction reduction may be determined by a combination of various factors. Particle size, crystal form, grinding aid, chemical bond\(^{[15]}\) and so on may help reduce the friction between the grinding ball and the material. When the grinding ball moves, it is easy to penetrate the material and hit the tank wall.

According to the relationship between the time change in the above figure and the number of peaks per minute, as shown in Table 1, the following figure exists.

| Time/min | Number of peaks /number |
|----------|------------------------|
| 30       | 69                     |
| 90       | 80                     |
| 150      | 101                    |
| 210      | 119                    |
| 270      | 138                    |
| 330      | 166                    |
| 390      | 156                    |
| 450      | 158                    |

From the table, it can be seen that similar to the particle size change rule we know, the particle size changes greatly in the early stage of ball milling, the number of peaks per minute also changes, and the particle size does not change significantly in the late stage. Its particle size distribution diagram is shown in Fig. 2 (where \(D_{10}=0.849\mu m\), \(D_{50}=2.473\mu m\), \(D_{90}=11.7\mu m\)), and the number of peaks does not increase significantly. Take the first 5 times of data for linear fitting, as shown in Figure 3.

Fig. 2 particle size distribution after the particle size is no longer significantly changed
The functional relationship between the number of peaks (y) and the change of time (x) can be roughly expressed as \( y = 0.322x + 54 \), and the variance r is 0.9868.

However, it is easy for us to know the particle size of the materials corresponding to each time, so the particle size of the materials in the tank at this time can be directly estimated according to the acoustic signals.

It is believed that the ball milling process can be roughly divided into three stages: in the first stage, most of the energy obtained by the grinding balls is used for crushing and grinding the materials, i.e. the energy is transferred from the grinding balls to the materials, which is manifested by the increase of the specific surface area of the materials, the larger friction force between the grinding balls and the materials, and the smaller impact sound and less frequent noise. In the second stage, parts of the energy participates in crushing and grinding, the friction between the grinding balls and the materials are weakened, and the grinding balls pass through the materials more easily and impact the tank wall of the ball milling tank, and this part of energy is converted into sound. In the third stage, the particle size of the material is already very small, and it is difficult to change significantly. At this time, the material becomes fluffy, the friction between the grinding balls and the material is further reduced, and the grinding balls penetrate the material more easily. Most of the grinding balls are easy to hit the tank wall of the ball-milling tank at this time, and most of the energy of the grinding balls is converted into sound energy, so the collected sound wave changes greatly.

4. Conclusions and Prospect

Experiments show that the combination of acoustic signal and ball mill can detect the change of material particle size in the ball mill tank through the change of acoustic wave. There is an obvious functional relationship between the two. Different ball mill systems may have different relationships. Based on the inversion of acoustic signal, the monitoring and improvement of ball mill process can be realized. Different ball milling systems may obtain different relations from those in Results Analysis and Discussion, but its basic theory is feasible. Different relations can be calculated according to different systems in actual production so that the relation can be used to predict the particle size of the materials in the tank under the condition where only acoustic signals are known.

In addition, grinding aids are usually added before ball milling in actual production activities, and grinding aids are usually polymers. A large amount of heat generated during ball milling will raise the temperature of materials and grinding aids, which will easily lead to failure of grinding aids at the later stage of ball milling. Therefore, in future production, the intelligent control system as shown in Figure 4 can be designed in conjunction with acoustic signal collector, temperature detector, computer and automatic control system.
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