Multi-particle crushing behaviors and characteristics via numerical simulations

Chang Liu¹, Zuobing Chen¹, Weili Zhang², Ya Mao¹, Weidong Ye², Chenggang Yang², Qiang Xie¹*

¹School of Mechanical and Electronic Engineering, Wuhan University of Technology, 122 Luoshi Road, Hongshan District, Wuhan 430070, China; C.LIU@whut.edu.cn
²Hefei Zhongya Building Material Equipment Co., Ltd, 61 Fozhang Road, Hefei 230601, China;
*Correspondence: q.xie@whut.edu.cn

Abstract. Crushing equipment is involved in cement, electric power, nonmetal and other industries. However, the multi-particle crushing behaviors and characteristics are essential to the crushing equipment performance. In this paper a numerical model for multi-particle crushing has been established in order to investigate the behaviors and characteristics of particle crushing. The evolution process of particle crushing, size effect, law of energy accumulation and dissipation were comprehensively discussed. The particle crushing behaviors are remarkable. when multiple particles were crushed, a large number of failure units and acoustic emission (AE) appeared at the top. The energy consumed by multi-particle crushing was low, and multi-particle crushing was more efficient. The particle size is of great importance to the crushing characteristics. The bigger a particle is, the easier the crushing happens. This study could give useful suggestions in the design of the crushing technology.

1. Introduction

In most beneficiation plants, the crushing process is a unit operation with high investment, high consumption, and large energy. The largest cost in the development of mineral resources comes from energy consumption. According to statistics, the energy consumption of ore crushing accounts for 30%-50% of the total production energy consumption [1-4]. Multi-particle crushing behavior is much more complicated than single one, and many scholars have done a lot of research. Wang's research on the theory of laminated crushing mainly summarized the theory of crushing dynamics and the law of energy consumption, and divided the crushing process into compaction stage, damage stage, crushing stage and material reunification stage [5]. Mütze [6] studied the stress behavior of lamination crushing, and concluded that the stress behavior is closely related to the compaction of the multi-particle. Kempton et al. [7] utilized the discrete element method (DEM) to simulate the compression process of particles in the packed bed, and explored the relationship between stress, porosity, number of fracture bonds and strain.

To study the characteristics of particle crushing efficiency and energy consumption, Zhao et al. [8] used numerical simulation methods to establish numerical models of single-particle crushing and multi-particle crushing of high-pressure roller mill. The simulation results show that the energy consumption required for multi-particle crushing is low and the crushing efficiency is high. In addition,
the particles in the middle of the particle group are crushed first than other surrounding particles and the crushing effect is obvious.

Numerical simulation is an important method to study particle crushing mechanism. The Swedish scholar Liu [9] discussed the crushing behavior of multi-particle during the extrusion process in a closed space by numerical simulation. It was found that large particles were squeezed by small particles with more contact points, which caused internal crack propagation when the compression displacement increased. The complexity of rock and soil leads to certain defects in many numerical simulation methods. In response to these problems, Tang proposed a numerical simulation method based on the analysis method of real rock fracture process [10].

In the above research, most scholars focused on the particle crushing behavior and characteristics. However, their physical models are quite different from those in this paper. For example, Wang and Mütze’s research on particle crushing process was obtained by crushing the particles in the closed area by a press [5,6]. Their crushing area is closed, and the particles will be squeezed by the closed cavity. However, the crushing area of the model in this paper is open, and the particles will only be subjected to vertical force. There is still a lack of research on this special crushing area at present. In addition, the method of describing particle crushing is relatively simple. Liu [9] and Zhao [8] did not make a comparison in terms of physical properties. Aiming at the special crushing area of the model in this paper, it is necessary to discuss the crushing behavior and characteristics of single-particle and multi-particle from the aspect of physical properties.

2. Numerical Model
In the process of rock crushing, the non-uniformity of the material has a great influence on the crack propagation and damage. Therefore, the inhomogeneity of geotechnical material should be considered in the micro modeling. This factor is considered in this paper, the mechanical properties of the elements that make up the simulation model satisfy the statistical distribution of Weibull function [10], given by

$$\varphi(\alpha) = \frac{m}{\alpha_0} \left(\frac{\alpha}{\alpha_0}\right)^{m-1} e^{-\left(\frac{\alpha}{\alpha_0}\right)^m}$$

where $\varphi(\alpha)$ is the statistical distribution density of the $\alpha$ (unit: MPa$^{-1}$), $\alpha$ represents the mechanical property parameters (strength, elastic modulus, etc.) of the rock medium primitive, $\alpha_0$ denotes the average value of the mechanical property of the primitive body, $m$ is the shape parameter of the distribution function, and its physical meaning reflects the homogeneity of the rock medium.

3. Multi-particle crushing description
Multi-particle crushing model is established, as shown in Fig. 1. 26 circular particles are randomly distributed in the numerical model, and the particle size is in the range of 10-45mm. The average particle size and distribution coefficient are 23.5mm and 1.45, respectively. The mechanical parameters are assigned according to the Weibull distribution. Based on the displacement loading method, the loading amount in Y direction is set 0.0015mm, and the loading step number is set 150 steps.
Fig. 1. Multi-particle crushing model diagram. All particles are marked with (1-26) numbers.

The stress loading step curve in Y direction of multi-particle crushing is shown in Fig. 2. It is quite different from the curve of single-particle, and seven characteristic points (a-g) are selected to analysis. It reveals that mechanical behavior of multi-particle crushing are much more complicated than single one, and the nonlinear fluctuations are more obvious.

![Stress loading step curve in Y direction of multi-particle crushing.](image)

Fig. 2. Stress loading step curve in Y direction of multi-particle crushing.

Fig. 3 shows the maximum principal stress diagram of 7 characteristic points (a-g) of multi-particle crushing. The AE diagram of 7 characteristic points of multi-particle crushing (a-g) is shown in Fig. 10. The AE energy release and AE accumulated energy release are shown in Fig. 5a, and Fig. 5b presents the AE counts and AE accumulated. Combined with Fig. 2 to Fig. 5 for a comprehensive analysis:

(1). It can be seen from Fig. 8 that the whole crushing process is consistent with the conclusion of Wang [5] on multi-particle lamination research and can be divided into three stages: compaction stage, damage stage and crushing stage. Fig. 3 shows that the continuous process of particles from micro damage to macro damage under the action of lamination. It is not difficult to find from Fig. 9 that the stress of particles at the contact point is larger than that in other areas, which indicates that the state of particle breakage is closely related to the contact point. Generally, the crack propagates along the contact point of one end of the particle to the contact point of the other end. It can be indicated from Fig. 4 that AE starts from the corresponding point a. With the increase of load, the AE phenomenon becomes more and more obvious. At point b, particles 3 and 26 have obvious macroscopic damage. At point d, particles 2 and 6 are destroyed obviously, and the compressive strength of particle layer is 13.317MPa. At point f, particles 5, 12, 15 and 16 are damaged obviously. All particles have different sizes of damage and destruction. It can be indicated from the Fig. 2 that particle 6 has basic element damage in the ab stage, but macro damage occurs in the cd stage. A similar behavior is found in particle 15, which means that the element damage of particles has been occurring with the increase of load until the particles are completely destroyed. It should be pointed out that the particles that have been partially destroyed will continue to produce element damage as the load increases.

(2). It can be obtained that from the Fig. 4 that large amount of failures are caused by tensile stress, and only a small part by compression and shear. It can be inferred that the multi-particle crushing of the vertical roller mill is mainly caused by tensile stress. The top and bottom particles are crushed first, then the middle particles, and the number of particles crushed at the top is the most. This
phenomenon is different from Zhao’s crushing law of the high-pressure roller mill’s particle layer [8], because the particles at the left and right ends of the particle layer of the vertical roller mill are in an open environment and are not squeezed, so the particles near the edge are not easy to be crushed. It is pointed out that small particles are more likely to be crushed than large particles, closely related to the stress state of small particles, and this conclusion is consistent with the results of Liu’s study [9].

(3). It can be found from the Fig. 11a and Fig. 11b that element failure and AE energy release behavior begin to occur at the loading step 27. Before the loading step reaches 124, the particles accumulate a large amount of elastic potential energy as the load increases until the crack expands to macroscopic destruction. During the process of elastic potential energy release, a large amount of AE energy is generated. The greater the energy released, the more intense the particle crushing. The conclusion can be drawn from the Fig. 5 that the cumulative energy of AE and the cumulative number of AE of multi-particle crushing are much larger than that of single-particle. It can also be seen that the relationship between the AE energy and AE counts is not linear, this is because the element’s elastic modulus and Poisson’s ratio of the elements are different. So resulting in different degrees of damage and different AE energy release.

Fig. 3. Maximum principal stress diagram of multi-particle crushing (the brighter the color is, the greater the stress value is).
Fig. 4. AE diagram of multi-particle crushing.

Fig. 5. (a) AE energy release and AE accumulated energy release diagram. (b) AE counts and AE accumulated counts diagram.

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