Numerical Study on Crushing Law of Iron Ore under Different Impact Velocity Using CDEM

Chun Feng¹², Xinming Liu¹², Xinguang Zhu¹², Xinquan Wang¹²
¹Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
²School of Engineering Science, University of Chinese Academy of Sciences, Beijing, 100049, China
fengchun@imech.ac.cn

Abstract. Ore crushing is one of the most important steps in mine engineering, and numerical simulation is a useful way to predict the crushing effect under impact load. Based on continuum discontinuum element method (CDEM), by introducing the linear elastic constitutive law into the element and the cohesive model into the virtual interface, the iron ore crushing simulation under different impact velocities was realized. The 2D single circular iron ore mesh and nine circular iron ores mesh with the diameter 3cm were established, the fracture and fragmentation process of iron ores under different impact velocities was simulated, and the evolution laws of fracture degree, damage degree, and the grading curve of fragments were obtained. The results show that, with the increase of impact velocity, the fragments of iron ores increase gradually; the bottom ore is crushed most seriously, while the top ore is damaged lightest, which demonstrates that the lower iron ores have an obvious buffering effect on the upper ores. In the single iron ore impacting case, when the impact velocity increases from 25m/s to 150m/s, the median particle size D50 decreases from 14.7mm to 2.2mm, the fracture degree increases from 1.6% to 28.9%, and the damage degree increased from 5.6% to 43.3%. In the nine iron ore impacting case, when the impact velocity increases from 50m/s to 150m/s, the fracture degree increases from 6.0% to 31.0%, the damage degree increases from 12.3% to 45.4%. When the impact velocity is 100m/s, the median particle size D50 at bottom, middle ant top part is 1mm, 3.6mm and 14.7mm, respectively. The above conclusions can provide basis for optimal design of impact crushing process of iron ore.

1. Introduction
Impact crushing is the most important ore crushing method. There are three classical theories to predict the fragmentation of ore under impacting load, namely, surface area theory, volume theory and crack theory [1-2]. Although these three theories play an important role on the prediction of crushing energy and fragmentation size, the dissipation of input energy and the damage process of ore are not well considered.

With the development of computer technology, numerical simulation has become an effective way to analyze the ore crushing process. Finite element method (FEM), discrete element method (DEM) and finite discrete element coupled method (FDEM, CDEM, DDA, et al) are three major numerical methods to simulate the ore crushing process. Thornton, et al[3] simulated the process of particle fragmentation under different impact velocities by DEM, and proposed that there was a critical impact velocity, which could divide the particle impact response into damage and fragmentation. Potyondy, et al[4] established...
the rock broken bond particle model based on DEM, which could represent many characteristics of rock behavior. Moreover, Potyondy suggested that macroscopic fracture was developed from broken bonds. Ning, et al.\textsuperscript{[5]} simulated the shear fracture process of circular particles, and studied the particle surface wear and particle overall crushing, which improved the particle crushing theory. Ma, et al.\textsuperscript{[6]} introduced the cohesive force model into FDEM, and thoroughly investigated the effects of particle breakage on the compressibility, shear strength, volumetric response of the fairly dense breakable granular assembly. Ma, et al.\textsuperscript{[7]} simulated uniaxial compression of rock particles by FDEM and computer tomography, and considered the dominant fracture mechanisms were related to the grain morphology. Feng, et al.\textsuperscript{[8]} discussed the dynamic constitutive curves, dynamic uniaxial compressive strength, energy consumption density, fracture degree, and fragments’ characteristic size of hematite based on CDEM. Li, et al.\textsuperscript{[9]} studied the dynamic strength, energy dissipation density and fragment size of limestone, dolomite and sandstone, respectively, and suggested that the increase of the crack density and the change of the crack propagation path were the mechanism of the dynamic fracture of the rock. Liao, et al.\textsuperscript{[10]} discussed the dynamic impact characteristics of rock under different loading conditions and studied the characteristics of rock materials under dynamic compressive and tensile loadings by RFPA. Li, et al.\textsuperscript{[11]} proposed a grain-based discrete element method (GB-DEM), and verified the fundamental pre-requisites of the SHPB technique. Li, et al.\textsuperscript{[12]} showed that the shape of rock specimen had little effect on rock failure mode through SHPB and numerical simulation test.

The crushing law studies for single particle ore and multi-particle ores under different impact velocities are the basis of ore crushing research. In order to represent the damage, fracture and fragmentation process of ores under impact velocity precisely, the continuum discontinuum element method (CDEM) will be adopted, and the relationship between crushing status and impact velocity will be discussed in detail. According to the simulation, the crushing pattern and degree of ores will be observed, and the affection of ores mutual collision will be clarified.

2. Numerical method and constitutive model

2.1. Introduction of CDEM

The continuum discontinuum element method (CDEM) is the combination of FEM and DEM, and it is suitable to simulate the progressive failure process of rock mass under dynamic load. The numerical domain in CDEM is discretized by finite elements and virtual interfaces (shown in Figure 1). Finite elements are used to represent the elasto-plastic behavior by introducing macro constitutive laws, and virtual interfaces are adopted to describe the damage and fracture features by adding breakable one-dimensional springs.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{elements and interfaces in CDEM}
\end{figure}

CDEM is an explicit time history-analysis approach and forward-difference approximation is adopted to solve the particle motion equation (Equation (1)) through a time marching scheme.

$$m \ddot{u} + c \dot{u} = F^E + F_c + F_d + F_t$$ \hspace{1cm} (1)

In equation (1), \(m\) and \(c\) are nodal mass and viscous damp coefficient, \(\ddot{u}\) and \(\dot{u}\) denote nodal acceleration and velocity vector, \(F^E\) means the external force vector applied on nodes, \(F_c\) and \(F_d\) are
deformation force vector and damping force vector induced by elements, $\mathbf{F}_d'$ and $\mathbf{F}_c'$ represent the deformation force vector and damping force vector induced by interface springs.

2.2. Elastic-damage-fracture constitutive model
To simulate the fragmentation process of rock mass precisely, linear elastic constitutive law is adopted in finite element, and the fracture energy model is introduced in virtual interface (Figure 2).

$$
\Delta \sigma_y = 2G\Delta e_y + \left(K - \frac{2}{3}G\right)\Delta \theta \delta_y
$$

(2)

$$
\sigma_y(t) = \Delta \sigma_y + \sigma_y(t_0)
$$

(3)

Where, $\sigma_y$ is the stress tensor, $\Delta \sigma_y$ means the incremental stress tensor, $\Delta e_y$ is the incremental strain tensor, $\Delta \theta$ is incremental volume strain, $K$ is the volume modulus, $G$ is the shear modulus, $\delta_y$ is Kronecker mark, $t_0$ represents the current time step, and $t_1$ represents the next step.

The fracture energy constitutive law in virtual interface could represent the tensile fracture and shear fracture induced by impact load. The trial normal and tangential spring force will be calculated first with time incremental algorithm.

$$
F_n(t_1) = F_n(t_0) - k_n \times A_c \times \Delta u_n
$$

(4)

$$
F_s(t_1) = F_s(t_0) - k_s \times A_c \times \Delta u_s
$$

Where, $F_n$ and $F_s$ are normal and tangential spring force, $k_n$ and $k_s$ mean normal and tangential spring stiffness per unit area (Pa/m), $A_c$ is the characteristic area of spring, $\Delta u_n$ and $\Delta u_s$ represent the normal and tangential incremental deformation of spring.

Equation (5) is adopted to correct the normal spring force and tensile strength.

$$
\begin{align*}
\text{if} & \quad -F_n(t_1) \geq \sigma_y(t_0) A_c \\
\text{then} & \quad F_n(t_1) = -\sigma_y(t_0) A_c \\
& \quad \sigma_y(t_1) = -(\sigma_y(t_0))^2 \times \Delta u_n / (2G_{ft}) + \sigma_{t_0}
\end{align*}
$$

(5)

Where, $\sigma_{t_0}$, $\sigma_y(t_0)$ and $\sigma_y(t_1)$ mean tensile strength of spring at initial stage, current time step and next time step, $\Delta u_n$ is the normal spring deformation at current step, and $G_{ft}$ denotes the tensile fracture energy (Pa.m).

Equation (6) is used to correct the tangential spring force and cohesion.

$$
\begin{align*}
\text{if} & \quad F_s(t_1) \geq F_s(t_0) \times \tan \phi + c(t_0) A_c \\
\text{then} & \quad F_s(t_1) = F_s(t_0) \times \tan \phi + c(t_0) A_c \\
& \quad c(t_1) = -(c_0)^2 \times \Delta u_s / (2G_{ft}) + c_0
\end{align*}
$$

(6)
Where, $\phi$ is inner friction angle, $c_0$, $c(t_0)$ and $c(t_1)$ mean cohesion of spring at initial stage, current time step and next time step, $\Delta u_s$ is the tangential spring deformation at current step, and $G_{fs}$ denotes the shear fracture energy (Pa.m).

Once the tensile strength or cohesion of a spring decreases to zero, the fracture occurs.

**3. Numerical model and parameters**

The single circular ore model and nine circular ores model were established, respectively (shown in Figure 3). The diameter of the iron ore was 3cm, and each ore was discretised by 30,000 triangular elements. In nine ores model, 9 ores were arranged in 3 rows and 3 columns, the gap between adjacent ores was 0.1mm. The rigid plate was set at the bottom, and downward impact velocity was applied on the ores.

**Figure 3.** Numerical models

In order to study the relationship between fragmentation and impact velocity, different impact velocities were adopted. In single ore model, five kinds of impact velocity were considered, with the value 25m/s, 50m/s, 75m/s, 100m/s, 120m/s, and 150m/s. In nine ores model, three kinds of impact velocity were used, with the value 50m/s, 100m/s and 150m/s.

The parameters of the iron ore are shown in Table 1.

**Table 1.** Parameters of iron ore

| Density /kgm$^{-3}$ | Elasticity modulus /GPa | Poisson’s ratio | Cohesion /MPa | Tensile strength /MPa |
|-------------------|------------------------|----------------|--------------|-------------------|
| 3200              | 60                     | 0.25           | 36           | 12                |

| Inner friction angle $\phi^\circ$ | Dilation angle $\phi^\circ$ | Tensile fracture energy /Pa.m | Shear fracture energy /Pa.m |
|----------------------------------|----------------------------|-------------------------------|---------------------------|
| 40                               | 10                        | 100                           | 500                       |

To evaluate the crushing degree quantitatively, fragments grading curve and median particle size $D_{50}$ were used, and fracture degree and damage degree were defined.

$$
D_f = \frac{A_f}{A_i} \\
D_d = \sum_{i=1}^{N} A_iD_i / A_i
$$

(7)

Where, $D_f$ and $D_d$ mean fracture degree and damage degree, respectively. $A_b$, $A_i$ are total fracture area and total area of virtual interface. $A_i$ and $D_i$ denote the area and damage factor of $i$th virtual interface. $N$ is the total number of virtual interface.

According to the individual block statistical algorithm, the volume and characteristic size for each fragment is obtained, and then the fragments grading curve could be formed. The median particle size $D_{50}$ is the particle size when the cumulative fragmentation distribution percentage of fragments reaches 50 %, which could be obtained by data interpolation.
4. Results of single ore model
The crushing status of ore in different impact velocities at same impact duration time are shown in Figure 4. The results show that, with the increase of impact velocities, the crushing degree increases sharply. When the impact velocity is 25m/s, the ore is broken into few large pieces by the control of vertical fracture surface. When the impact velocity reaches 150m/s, the ore is broken into large number of small pieces, and the crushing degree of bottom part is significantly higher than the top part.

![Figure 4. Crushing status of single ore model in different impact velocities (duration time = 208 us, different colour means different fragments)\(\)](image)

The variation of fracture degree and damage degree under different impact velocity are shown in Figure 5~7. The results show that, with the increase of impact velocity, the fracture degree and damage degree increases linearly. When the velocity increases from 25m/s to 150m/s, the fracture degree increases from 1.6% to 28.9% and the damage degree increases from 5.6% to 43.3%. From Figure 5-6, the time history of fracture degree and damage degree could be divided into two stages. The first stage is from 0us to 25us; in this stage, the fracture degree and damage degree increases sharply. The second stage is from 25us to 250us; in this stage, the increasing speed of fracture degree and damage degree drops down gradually.

![Figure 5. Variation of fracture degree with impact time (single ore model)\(\)](image)

![Figure 6. Variation of damage degree with impact time (single ore model)\(\)](image)

![Figure 7. The relationship between fracture degree, damage degree and impact velocity\(\)](image)
The fragments grading curve and median particle size D50 under different impact velocity are shown in Figure 8 and Figure 9. From these two figures, the higher of the impact velocity, the smaller of the fragments size. When the impact velocity increases from 25m/s to 150m/s, the D50 decreases from 14.7mm to 2.2mm.

Figure 8. Fragments grading curve under different impact velocity (single ore model)

Figure 9. The relationship between median particle size D50 and impact velocity

5. Results of nine ores model

The crushing status under different impact velocity at same impact duration time is shown in Figure 10. From this figure, with the increase of impact velocity, the crushing degree increases gradually. The three ores at the bottom are broken most seriously, while the top ores are crushed most slightly, so the buffer effect of the lower ores on the upper ores is obvious.

Figure 10. Crushing status of nine ores model in different impact velocities (duration time = 426 us, different colour means different fragments)

The variation of fracture degree and damage degree of the model with the impact duration time are shown in Figure 11 and Figure 12. From these two figures, with the increase of impact velocity, the fracture and damage degree increases gradually. When the duration time is from 0us to 100us, the fracture and damage degree increases sharply. While the duration time is larger than 100us, the increasing speed of fracture degree and damage degree is slower gradually. When the duration time is larger than 300us, the fracture degree and damage degree are basically stable.

Figure 11. Variation of fracture degree with impact time (nine ores model)

Figure 12. Variation of damage degree with impact time (nine ores model)
The fragments grading curves under different impact velocity are shown in Figure 13. From this figure, with the increase of impact velocity, the fragments size of the model decreases gradually. When the impact velocity is 50m/s, the grading curve of middle row is more similar to the top row. While the impact velocity reaches 150m/s, the grading curve of middle row is more similar to the bottom row. Under the low impact velocity, the middle column ores are crushed more serious compared with the side ores due to the two side collision. However, under the high impact velocity, the fragment size of the middle column ores is lager then the side ones due to the lack of deformation space induced by the lateral extrusion (top row is an exception).

Figure 13. Fragments grading curve under different impact velocity (nine ores model)

6. Conclusion
Based on the continuum discontinuum element method (CDEM), by introducing elastic-damage-fracture constitutive law, the crushing status of ores under different impact velocity are discussed in detail. Numerical results show that:

1. With the increase of impact velocity, the fracture degree and damage degree increases gradually, and fragments size decreases gradually;
2. In single ore model, when the impact velocity increases from 25 m/s to 150 m/s, the median particle size D50 decreases from 14.7 mm to 2.2 mm;
3. In single ore model, when the impact velocity increases from 25 m/s to 150 m/s, the fracture degree increases from 1.6% to 28.9%, and the damage degree increases from 5.6% to 43.3%;
4. In nine ores model, the three ores at the bottom are broken most seriously, while the ores at the top are crushed most slightly, the buffer effect of the lower ores on the upper ores is obvious.

According to the numerical results, in the process of ore impact crushing, the impact velocity can be adjusted by the required ore product size. Since the crushing effect of single particle ore is better than the effect of multi-layer ore, in order to achieve better crushing effect, multi-layer ore superposition should be avoided as far as possible in actual production. This paper has a certain guiding effect on the actual production of ore impact crushing.

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