Computer Simulation Methods for Crushing Process in an Jaw Crusher

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Abstract. One of the trends at modern mining enterprises is the application of combined systems for extraction and transportation of the rock mass. Given technology involves the use the conveyor lines as a continuous link of combined technology. The application of a conveyor transport provides significant reduction of costs for energy resources, increase in labor productivity and process automation. However, the use of a conveyor transport provides for certain requirements for the quality of transported material. The maximum size of the rock mass pieces is one of the basic parameters for it. The crushing plants applies as a coarse crushing followed by crushing the material to the maximum size of piece which possible to use for conveyor transport. It is often represented by jaw crushers. Modelling of crushing process in jaw crushers allows to maximally optimize workflow and increase efficiency of the equipment at the further transportation and processing of rocks.

We studied the interaction between walls of the jaw crusher and bulk material by using discrete element method (DEM) in this paper. The article examines the process of modeling by stages. It includes design of the crusher construction in solid and surface modeling system. Modelling of the crushing process based on the experimental data received via the crushing unit BOYD. The process of destruction and particle size distribution in the study was done. Analysis of research results shows a comparability of actual experiment and modeling process.

1. Introduction.
Preparation of a rock mass for enrichment includes quite energy-intensive process of crushing. Initially, the rock mass crushing made by drilling and blasting operations. The next stage to reduce the medium size of rock mass pieces used crushing plant for coarse splitting. The next stage to reduce the medium size of rock mass pieces is the use of crushing plant for coarse splitting. It is mostly provided by jaw crushers. Among the various crushing equipment jaw crushers are widely used. The advantages of jaw crushers are simplicity of the design, reliability, small overall dimensions and weight, as well as easy maintenance and repairing. Disadvantages of jaw crushers is a periodical operation mode and availability of large swinging masses.

We studied the interaction between walls of the jaw crusher and bulk material by using discrete element method (DEM) in this paper. Operations via ball mills, autogenous and semiautogenous grinding mill rather widely describes in the scientific literature [1-4]. Whereas modeling of jaw
crushers is possible to find only a small amount of articles actually [5,6,7,8]. Modeling of the grinding operation in a jaw crusher is an exciting and actual problem.

The jaw crushers have proliferated among the various crushing equipment. It is used for coarse crushing.

Modeling of crushing process allows to select the most effective mode of equipment operation. Also it allows to study process of breaking visually and "from the inside". DEM is one of the new instruments for research of the destruction process for various materials [8,9,10]. In recent years this approach quickly became a powerful and effective instrument of modeling. The fundamental assumption of this method is that matter is composed of separate discrete particles. This method is based on representation of material as the aggregate of interacting particles (usually it is spherical particles). It is moving according to Newton's classical laws with taking into account the external force fields (there is gravity, friction, momentum and elastic interaction). DEM allows to get comprehensive data of an arbitrary particle at moment of interest: location, operating force, speed, acceleration, direction of movement and energy of the particle.

DEM calculation cycle represents as a step by step calculation per unit time, over which the law of motion is applied to each particle and each contact surface. The boundary conditions are updated in the modeling process. The interaction between the elements formed and stopped automatically. DEM calculation cycle in the general form is shown in Figure 1. During one modeling step calculation is performed with average range from $10^{-8}$ to $10^{-6}$ seconds.

![Figure 1. Calculation cycle](image)

Using the DEM requires rather simple, but very high demands on computer performance. Moreover, it is need to use modern software systems for maintenance of system flexibility with the ability to operative change parameters of the model, for parametrical optimization, to adding new properties into the model, to testing number of structures in order to select the most effective solutions.

The Rocky software package [12] has been selected for modeling of technological processes with bulk materials and applicable equipment as such an instrument among variety of different software packages and available integrable platforms [10,11] in existence today. Modeling has been done by using a workstation in a specialized laboratory of the Automation of technological processes and production facilities department of the National Mineral Resources University (University of Mines).
We have made review of the literature and analyzed data of physical experiments in production conditions using crushing plants at the same time.

2. Modeling
Modelling of crushing process is restricted in a jaw crusher work area. It is the area where the grinding of the material and movement of adjacent geometric surfaces (cheek crusher) does. Modelling of the crusher design produced in real scale by used solid and surface modeling system of the SolidEdge [13]. Design details which complicate the process of modeling or not involved in it (for example: the shaft, the frame, connecting rod, etc.) not included in the three-dimensional model. Using the Solid Edge as a three-dimensional modeling environment enables not only to make the construction of the model, but it also allows you to quickly and efficiently make any modification to the design of the model. Subsequently, the created model can easily be imported in the ROCKY (Fig. 2).

![Jaw crusher in Rocky](image)

Figure 2. The jaw crusher BOYD in the Rocky, which contains processed material

3. Modelling of material for research
The structural concrete as a material was selected for fragmentation. This material is widely available and its properties are well understood. Rocky Software features allow you to set many parameters generated particles (Table 1). Unlike many other tools for modeling using the MDE, which use either spherical particles or other pre-form [14, 15] in Rocky has an option to select an arbitrary particle geometry. This allows the maximum to take into account features of the material used and the structure at failure.

| Parameter               | Value               |
|-------------------------|---------------------|
| Rotation of particles   | Yes                 |
| Rolling resistance      | 0                   |
| Vertical aspect ratio   | 1,50                |
| Horizontal aspect ratio | 0,75                |
| Number of corners       | 25                  |
| Density                 | 1600 kg/m³          |
| Loading Stiffness       | 1*10⁸ N/m²          |
| The bulk density        | not taken into account |
The complex polygon shape has been selected as the particles (Fig. 3)

Figure 3. The shape of the processed material particles.

For each particle in contact with other particles and / or geometric surfaces calculated total energy density of this contact. If this energy is greater than the minimum energy of the particle destruction \( E_{\text{min}} \), the \( E_{\text{min}} \) defined as

\[
E_{\text{min}} = E_{\text{min},r} \left( \frac{L_r}{L} \right)
\]

(1)

where \( L \) - particle size,
\( E_{\text{min},r} \) the minimal specific energy for the average particle size for the selected material (this material constant)
\( L_r \) - average particle size, minus the minimum energy added to the total energy of the previous contacts \( E_{\text{sum}} \):

\[
E_{\text{cum}} = E_{\text{cum}} + E - E_{\text{min}}
\]

(2)

Particle fracture probability \( P \) is calculated by the formula [16]:

\[
P = 1 - \exp \left( -S \cdot \left( \frac{L}{L_r} \right) \cdot E_{\text{cum}} \right)
\]

(3)

where \( S \) - the parameter of the particle breakage strength.

If the particle is destroyed, then fragments are generated by an algorithm Voronoi fracture [17] in accordance with the distribution indicated by the built-in functions \( T_{10} \):

\[
T_{10} = M \cdot (1 - \exp \left( -S \cdot \left( \frac{L}{L_r} \right) \cdot E_{\text{cum}} \right))
\]

(4)

where \( M \) is a constant for the selected material. The size distribution of fragments of the wreckage determined from the value of \( T_{10} \). The distribution of particle size is calculated based on the model Gaudin-Schumann [18], where the mass fraction of particles retained in each calculation interval calculated by an equation with two given constants:

\[
W_p = 100 \cdot \left( \frac{x}{k} \right)^m
\]

(5)

Where \( W_p \) - mass yield,%
\( x \) - particle size,
\( k \) - particle size constant
\( m \) - distribution constant

Table 2 – The modeling parameters

| Parameter                  | Value |
|----------------------------|-------|
| Minimum Size               | 0,005 m |
| Reference size             | 0,007 m |
| Minimum specific energy    | 0 J/kg |
| Select function coefficient| 1 J/kg |
| Maximum T10 value          | 10,00 |

Note that in the above Tables 1 and 2 list only a few parameters of the simulation. Functionality of the program covers more of the properties of elements and process parameters.

Furthermore, it is necessary to consider the number of particles participating in the simulation. When splitting the number of particles increases several times compared with the initial state, while
significantly increasing the calculation time model. For example, for numerical processing only 1000 particles require about 20 hours of computation on a workstation with 9 cores.

4. Modeling the dynamics of movement of the cheeks

In crushers with a complex movement the movable jaw fixed to the eccentric portion of the main shaft, further acting as a connecting rod. At the bottom of the connecting rod is attached to the spacer plate that can oscillate around a fixed point. With this consolidation, by the rotation of the main shaft, each point of the movable jaw will describe the trajectory of a closed curve in the form of elongated ellipses. At this point the trajectory will have lower longitudinally extending closed curves, and when approaching the top of the trajectory of the movable cheek increasingly will approach the form of a circle. When approaching a stationary cheek occur simultaneously lower the movable jaw down.

material other than grinding exposed on the impacts from the stekni cheeks, so that there is a material and pushing it easy abrasion. In other words there is involuntary discharge of the crushed material.

Therefore, with the same overall dimensions of the crusher with a complex motion more productive. It is this feature of crushers with a complex movement of interest for modeling and optimization. The software package allows for complex motion, adjusting the parameters such as frequency and amplitude of the motion.

In addition to movement crusher jaws considered the physical characteristics of the surface and, if necessary, it is possible to control the deterioration of "jaw armor", thus predicting the area exposed to the greatest abrasion.

5. Calibration and experiments

For the simulation of the crushing process, first of all, you need to calibrate the static parameters. Estimate the actual state of the particles as a result of crushing, particle size distribution and the number of degrees of freedom.

We create the data for the calibration setting parameters of the material, making a comparison between experiment and simulation. Thus, one should always pay attention to portability of simulation results for process parameters such as particle size distribution and specific energy consumption. The next step is to change the model parameters as long as they will not reflect reality. Maximum use of the actual specific characteristics and process parameters are always gives a good foundation for the rapid and successful simulation. The sequence of the calibration procedure is described in detail in [19, 20].

| Experiment | Table 3 – Parameters of the experiment and the model |
|------------|-----------------------------------------------------|
| Aggregate  | Around 1200 of the particles                        |
| $\rho$=1600 kg/m$^3$ | $\rho$=1600 kg/m$^3$ |
| $d$=0,1…16 mm | $d$=5…16 mm |
| $E$=30…40 kN/mm$^2$ | Stiffness aggregate $k=6 \cdot 10^6$ N/m |
| Compression strength $\sigma_n > 35$ N/m | Normal strength $\sigma > 1.5 \cdot 10^7$ N/m$^2$ |
| Coefficient of friction concrete-steel $\mu \approx 0.3$ | $\mu = 0.3$ |

Experimental data [13, 20] was used in the subsequent model calibration and verification of simulation results. A large number of experiments on the jaw crusher were carried out to investigate conditions for concrete recycling. The obtained experimental data could also be used for calibrating the DEM models and validating the results. Following process parameters were varied: the feeding rate of the concrete pieces between 4.5 and 13.3 t/h which corresponds to the volume fraction of solids in the process area of 2.6 to 12.4%, the smallest gap width between 20 and 35 mm and the peripheral rotor speed between 25 and 38 m/s. Test samples of the material were only a concrete pieces shaped complex polygons.
Figure 4 shows a comparison of experimental data and simulation results. The graph shows the distribution of particle size obtained milled products. Experimental distribution curves shown in the figure, are correlated in order. The higher rotor speed, the smaller the resulting product respectively. Simulation curve lies below the rest of the experimental data, since the minimum size of the simulated particle was 5 mm. Selecting this particle size was primarily limited time settlement models.

6. Conclusions and prospects
Simulation of crushing using jaw crusher is only one of many examples of the application of the DEM. The features of this simulation can be the basis of material intended for a more detailed study of the process in view of a more detailed experimental data.

It is noteworthy that the amount of time for calculations increases sharply with the number of particles and largely determines the accuracy of the results. Therefore, new methods must meet the following conditions:

1. Interaction of specialized software allows you to quickly change the design elements and optimize the operation of the unit. The simulation results can be instantly imported for further careful evaluation.

2. In the simulation process, it is impossible to take into account a disproportionately large number of particles generated as a result of crushing, resulting in a significant increase in computation time. Smaller particles in particular occur in vast numbers and make the calculation last much longer. Hence, their interaction with other particles and walls can hardly be simulated. A pressure term, obtained from the Maxwell velocity distribution, replaces their interaction forces so that they do not need to be simulated. It can be predicted that the computing time will be saved remarkably.:  

List of accepted designations.

| Designation | Description                                           |
|-------------|-------------------------------------------------------|
| DEM         | discrete element method                               |
| L           | particle size,                                        |
| $E_{min.r}$ | the minimum specific energy of the average particle size for the selected material (material constant ) |
\( L_r \) – average particle size, minus the minimum energy added to the total energy of the previous contacts \( E_{\text{sum}} \).

\( S \) – breaking strength of particles.

\( E_{\text{min}} \) – the minimum energy for particle destruction.

\( P \) – probability of particle destruction.

\( M \) – constant for the selected material.

\( T_{10} \) – the function for calculating of particle destruction.

\( W_p \) – mass yield, %.

\( x \) – particle size,

\( k \) – constant of particle size.

\( m \) – distribution constant.

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