Optimization Design and Simulation Analysis for Cavity Shape of Single Toggle Jaw Crusher

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Abstract. The lower part of the crushing chamber of the single toggle jaw crusher is easy to block when it is used, which directly affects the capacity of the crusher and the service life of the moving jaw plate. The cavity shape of PE1500×1800 single toggle jaw crusher is taken as the research object, and Genetic Algorithm is used to optimize the design of cavity shape by taking the minimum difference of the open-side trapezoidal area between the crushing layer and the discharge layer at the lower part of the crushing chamber as the objective function. On the basis of the optimization design, the virtual prototype model of crusher's working device before and after the optimization is established based on ADAMS, and the motion characteristics of the moving jaw are simulated and analyzed. The simulation results show that the capacity of the optimized crusher is increased by 25.19% while the blockage is reduced, and the movement characteristics of the moving jaw discharge port are also improved.

1. Introduction
Single toggle jaw crusher is the most widely used crushing equipment in China because of its simple structure, economy and good operation. The crushing process of the crusher to the material occurs in its crushing chamber. The cavity shape of the crushing chamber plays a key role in the operation, technical indexes and product characteristics of the crusher[1]. The crusher with the linear crushing chamber has the same nip angle from top to bottom, which causes the material quality of each crushing layer to be different. Therefore, the lower part of the crushing chamber is easy to block when crushing solid materials, which not only reduces the capacity of the crusher, but also reduces the service life of the moving jaw liner. In view of the above problems of the crusher, this paper uses Genetic Algorithm to optimize the cavity of the single toggle jaw crusher, and simulates and analyzes the working equipment of the crusher before and after optimization, in order to reduce the incidence of material blockage and improve the capacity of crusher.

2. Principle of Layered Crushing of Jaw Crusher
According to the cavity shape and performance value of moving jaw track, the crushing cavity of jaw crusher is divided into several crushing layers along the vertical direction, as shown in figure 1[2]. When the crusher works, the moving jaw swings periodically around the suspension mandrel under the action of the eccentric shaft, when the moving jaw moves from the closed side to the open side, the closed side width of layer $i$ is equal to the open side width of layer $i - 1$, so the materials of layer $i$ fall into the layer $i - 1$ under the action of its own gravity, waiting for the next cycle to break[3]. The material in the discharge layer (layer 0 in the figure) is discharged from the discharge port to complete crushing.
3. Optimization Design Model of Cavity Shape of Jaw Crusher

3.1. Objective Function

As shown in Figure 2, the bottom width of layer $i$ is $b_i$, the top width of this layer is $b_{i+1}$, the height is $H_i$, the $\gamma_i$ is the moving jaw inclination of layer $i$, the $\delta_i$ is the fixed jaw inclination of layer $i$, the $s_i$ is the horizontal stroke of $C_i$ point on the jaw surface of layer $i$, and the $h_i$ is the difference between the vertical heights of $C_i$ and $C_i'$ of the moving point corresponding to $s_i$, then the open-side trapezoid area of layer $i$ is:

$$ A_i = b_i H_i + \frac{H_i^2 (\tan \gamma - \tan \delta)}{2} \tag{1} $$

According to the principle of layered crushing, to reduce the incidence of blockage in the lower part of the crushing chamber, it is necessary to make the material quality of each crushing layer tend to be equal. Because the filling degree of the materials to be crushed is not directly related to the performance value of the moving jaw surface, and the change along the cavity height is small, we can assume that the material filling degree of each crushing layer in the lower part of the crushing chamber is equal. At this time, the quality of each layer is directly determined by the trapezoid area of the opening side of the crushing layer.

The RMS of the trapezoid area difference between each crushing layer and discharge layer is:

$$ f(x) = \sqrt{\frac{\sum_{i=0}^{n} (A_i - A_0)^2}{n}} \tag{2} $$

The optimum chamber profile design is based on the smallest difference in trapezoidal area between the open sides of each crushing layer and its adjacent lower layer. So the objective function is:

$$ Q = \min f(x) \tag{3} $$

3.2. Design Variables

The blocking of jaw crusher mainly occurs in the lower part of the crushing chamber, and the closer it is to the discharge port, the more serious it is. The cavity shape of the crushing cavity is mainly determined by the moving and fixed jaw inclination of each crushing layer. Therefore, the moving and fixed jaw inclinations of the four crushing layers in the lower part of the crushing chamber close to the discharge port are taken as design variables. The design variable $X$ is expressed as:

$$ X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{bmatrix} = \begin{bmatrix} \gamma_0 \\ \delta_0 \\ \gamma_1 \\ \delta_1 \\ \gamma_2 \\ \delta_2 \\ \gamma_3 \\ \delta_3 \end{bmatrix} \tag{4} $$
3.3. Constraint Conditions
If the inclination of the moving and fixed jaw is too large, the moving jaw will interfere with the fixed jaw when it is close to the fixed jaw. According to the structure size of the crusher, the limits of the moving and fixed jaw inclination are:

\[ 10^\circ \leq \gamma_i \leq 40^\circ \]
\[ -5^\circ \leq \delta_i \leq 10^\circ \]  

(5)

According to friction theory and mechanics theory, it can be concluded that the nip angle of the single toggle jaw crusher in the working process isn’t larger than 24°, but it should not less than 18° either[4]. So the dip angle constraint is:

\[ 18^\circ \leq \gamma_i - \delta_i \leq 24^\circ \]  

(6)

The height constraint of the crushing layer is:

\[ H_i \leq H_0 \]
\[ \sum_{i=1}^{n} H_i \leq \frac{H}{3} \]  

(7)

Where \( H \) is the total height of the crushing chamber.

4. Application of Genetic Algorithm
Genetic Algorithm which simulates descendibility and evolution of biologist in nature environment forms a searching method of adapting all-round optimize probability. Genetic has been applied in many fields[5]. When optimizing the cavity shape of \( PE1500 \times 1800 \) single toggle jaw crusher, the parameters of Genetic Algorithm are: population size \( n=50 \), crossover rate \( pc =0.8 \), and mutation rate \( pm =0.09 \), termination generation \( T=200 \). The results of cavity shape optimization are shown in table 1:

Table 1. Moving, fixed jaw angle and dip angle of each layer after optimization.

| Number of crushing layer | Inclination of moving jaw(°) | Inclination of fixed jaw(°) | Dip angle of layer(°) |
|--------------------------|------------------------------|----------------------------|----------------------|
| 0                        | 13.00                        | -5.00                      | 18.00                |
| 1                        | 21.15                        | -0.79                      | 21.94                |
| 2                        | 30.02                        | 6.73                       | 23.23                |
| 3                        | 40.00                        | 19.00                      | 21.00                |

From table 1, it can be seen that the difference of open-side trapezoidal area of each crushing layer is the smallest when the average inclination of the moving jaw in layers 0~3 is 13°, 21.15°, 30.02°, 40°, and the average inclination of the fixed jaw is -5°, -0.79°, 6.73°, and 19°.

5. Simulation Analysis of Jaw Crusher
5.1. Building of Simulation Model
The working device of single toggle jaw crusher is mainly composed of eccentric shaft, moving jaw, toggle plate and frame, which is a crank-rocker mechanism, and crank, rocker, connecting rod correspond to eccentric shaft, toggle plate, moving jaw respectively in crusher. The mechanism diagram of \( PE1500 \times 1800 \) single toggle jaw crusher is shown in figure 3, and its structure size is: crank length \( L_1 = 32\text{mm} \), connecting rod length \( L_2 = 2730\text{mm} \), rocker length \( L_3 = 895\text{mm} \), frame length \( L_4 = 2290\text{mm} \).
Figure 3. Mechanism diagram of single toggle jaw crusher.

In the kinematic analysis, only the factors related to motion are considered, and it has nothing to do with the specific shape of the component[6]. Therefore, the working device of the single toggle jaw crusher is simplified without affecting the simulation results, and the simulation models of the working device before and after optimization are established by ADAMS. Then, adding revolute pairs between the frame and the eccentric shaft, the eccentric shaft and the moving jaw, the moving jaw and the toggle plate, the toggle plate and the frame based on the working principle of the double pendulum jaw crusher; add fixed pairs between the frame and the ground, between the fixed jaw and the ground; add the driving moment to the eccentric shaft. The simulation model before and after crusher optimization is shown in figure 4.

Figure 4. Simulation model of jaw crusher.

5.2. Kinematics Simulation Analysis of Moving Jaw

5.2.1. Comparison of blocking degree before and after optimization

Establishing marker points at the lower of each crushing layer before and after optimization, the horizontal stroke $s_i$ of each marked point and the difference $h_i$ between the vertical heights corresponding to the horizontal stroke is obtained through kinematics simulation analysis. The specific values are shown in table 2.

| Number of crushing layer | $s_i$ before optimization (mm) | $h_i$ before optimization (mm) | $s_i$ after optimization (mm) | $h_i$ after optimization (mm) |
|--------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 0                        | 46.76                         | 108.05                        | 47.16                         | 106.53                        |
| 1                        | 41.58                         | 104.58                        | 40.06                         | 102.81                        |
| 2                        | 37.23                         | 100.93                        | 35.90                         | 97.95                         |
| 3                        | 33.71                         | 94.52                         | 33.04                         | 93.99                         |

By substitution of the data in table 2 obtained from Kinematics simulation analysis into equation (6), the open-side trapezoidal area of 4 crushing layers at the lower part of the crushing chamber before and after optimization are calculated to be shown in table 3.
Table 3. Trapezoid area of each crushing layer before and after optimization.

| Number of crushing layer | Crushing layer area before optimization(mm²) | Crushing layer area before optimization(mm²) |
|--------------------------|---------------------------------------------|---------------------------------------------|
| 0                        | 39209.91                                    | 55780.10                                    |
| 1                        | 54432.03                                    | 55777.06                                    |
| 2                        | 66275.62                                    | 55777.21                                    |
| 3                        | 74424.70                                    | 55781.59                                    |

It can be seen from table 3 that the difference in the open-side trapezoidal area of each crushing layer at the lower part of the crushing chamber before optimization is large, and the closer to the discharge opening, the greater the difference, which is consistent with the actual blocking situation of the crusher. After optimization, the trapezoidal area of each crushing layer is basically equal, the material blocking phenomenon is improved, and the predetermined optimization goal is achieved.

5.2.2. Comparison of mechanism characteristics before and after optimization

Marking points is established at the discharge opening of the moving jaw of the simulation model before and after optimization. After the dynamic simulation, the curves of the horizontal displacement and the vertical displacement of the discharge port before and after optimization are output. The displacement curves of the discharge port are shown in figure 5.

![Displacement curves of the discharge port.](image)

According to the simulation results, the horizontal stroke of the discharge opening after optimization is increased from 46.7564mm to 47.1619mm, an increase of 2.40%; the vertical stroke is decreased from 108.0457mm to 106.6503mm, a decrease of 1.31%; moderately increasing the horizontal stroke of the moving jaw is conducive to improving the capacity of the crusher, and moderately reducing the vertical stroke of the moving jaw is conducive to decreasing the wear of moving jaw liner. In conclusion, the motion characteristics of the jaw discharge port of the crusher have been improved after optimization.

5.2.3. Comparison of capacity before and after optimization

The capacity of jaw crusher is calculated by swinging the jaw once and discharging a loose prismatic volume of ore from the crushing chamber, that is, the capacity is equal to the product of material crushed by the moving jaw in one swing cycle and the spindle speed. Then the expression of capacity Q is:

\[
Q = \frac{30n\sigma_0L(2b-s_0)\mu}{\tan \alpha_0}
\]

Where \( n \) is the spindle speed; \( L \) is the length of the crushing chamber; \( \mu \) is the filling degree of the compressed prism; \( \alpha_0 \) is the average nip angle of the discharge layer.

According to equation (11), the capacity of the crusher after optimization is increased from 167.91m³/h to 210.20m³/h, with an increase of 25.19%.

6. Conclusions

(1) Adopting a curve-cavity crusher, the open-side trapezoidal area of each crushing layer tends to be equal through changing the moving and fixed jaw dip of each crushing layer. At this time, the material
quality of each crushing layer is equal, so the blocking of crusher is greatly improved, which provides a theoretical basis for the improvement of crusher.

(2) From the simulation results, it can be seen that after optimization, the horizontal stroke of the crushing jaw discharge port increases by 2.40%, while its vertical stroke decreases by 1.31%, the motion characteristics of moving jaw have been improved.

(3) Because the nip angle of the discharge layer after optimization is small and the horizontal stroke is large, through theoretical calculations, it is known that the optimized crusher has increased the capacity by 25.19% compared with that before optimization.

7. References

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