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Analysis on the influence law of traction speed on the cutting performance of coal containing hard concretion

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Abstract. Due to the great differences in mechanical properties between hard concretion and coal, the shearer drum cutting coal and rock containing hard concretion will inevitably lead to a series of problems, such as severe load impact, increased cutting specific energy consumption and low coal loading efficiency. Taking the cutting part of a thin coal seam shearer in service in the target mining area as the prototype, the mechanical models of shearer drum and rocker arm are established by using UG, and the discrete element model of coal wall with hard concretions is built by importing it into EDEM. The influence law of traction speed on coal loading rate, drum load and cutting specific energy consumption is analyzed, and the corresponding fitting relationship function is obtained. Taking the traction speed as the design variable, and the drum load, cutting specific energy consumption and coal loading rate as the comprehensive indicators, a multi-objective optimization function is established. The optimal solution is obtained by using NSGA II optimization algorithm, and the accuracy of the simulation is verified by experiments. This method has certain engineering significance for the reasonable selection of shearer traction speed.

Keywords: Hard concretion / traction speed / coal loading rate / specific energy consumption / multi-objective optimization

1 Introduction

With the continuous completion of medium-thick high-quality coal seam mining and the increasing shortage of coal resources in east China, South China, southwest China and northeast China, it is imperative to study the efficient mining of complex thin coal seam in order to realize the requirements of healthy and coordinated development of mining area in the "14th Five-year Plan for Mine Safety Production". However, due to the narrow working space of the shearer, the complex geological structure, the coal seam contains a large number of hard concretions and gangue, etc., the problems of low coal loading rate, poor cutting performance and high energy consumption generally exist in the mining operation of the shearer. These problems are not only related to the geological structure, but also to the mechanical structure and kinematic parameters of the shearer. For the current shearer, adjusting the traction speed can improve the comprehensive performance of shearer cutting coal with hard concretion, thus reducing the energy consumption required by drum, improving the coal loading effect and cutting performance. Therefore, domestic and foreign scholars have done the following research.

1.1 Research on cutting specific energy consumption of drum

In 2006, Bilgin [1] established a series of rock samples with different compressive strengths and analyzed the cutting specific energy consumption of the drum, and obtained the accuracy of experimental and theoretical values; In 2008, Liu [2] established a mathematical model of the relationship between cutting specific energy consumption and motion parameters of the drum based on cutting theory of shearer. The proportional changing law of cutting specific energy consumption to traction speed is analyzed. In 2017, Li [3] analyzed and studied the influence of shearer motion parameters on cutting specific energy consumption. The linear relationship between cutting energy consumption and traction speed is obtained. In the same year, Zhang [4] established the kinetic model of the cutting unit and the cutting specific energy consumption model of the drum, and analyzed the changing rules between traction speed and specific energy consumption of the drum; In 2018, Gabov [5] analyzed the optimal match between cutting speed and cutting specific energy consumption, considering the energy consumption of the pick; In 2020, based on discrete element analysis of shearer spiral drum cutting coal and rock numerical simulation, Zou [6] concluded that the cutting

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specific energy consumption decreases with the increase of traction speed; In 2021, Zhao [7] analyzed the influence trend of shearer traction speed on the drum by single factor test method, and predicted the cutting performance of the spiral drum by using genetic algorithm – reverse transfer network, and the maximum relative error was 3.12%. In the same year, Zhang [8] adopted discrete element method and analyzed that the cutting specific energy consumption of the drum increased first and then decreased with the increase of the drum's traction speed.

1.2 Research on the effect of drum coal loading rate

In 1980, Morris [9] used computer aided technology to calculate the coal loading performance of the designed shearer drum, and obtained a better coal loading effect; In 1997, Shen [10] studied the distribution law of coal and rock particles cut by drum, and obtained the law that the lump coal rate decreases with the increase of traction speed; In 2017, Jin [11] adopted uniform design method to verify the reliability of shearer running at the optimal traction speed, and confirmed that the comprehensive mining performance of shearer can be guaranteed at the cost of appropriately reducing productivity; In 2018, Xu [12] obtained the optimal value of the influence of traction speed on the drum coal loading efficiency through orthogonal experiment; In 2019, Zhao [13] analyzed the similarity relationship between drum loading rate and derivation based on similarity theory, and verified the correctness of drum similarity criterion; In the same year, Gao [14] obtained the law that the traction speed affects the coal loading rate of the drum by affecting the filling rate of the cut coal in the drum by using the method of modeling test; Chen [15] established a model based on cutting specific energy consumption, production efficiency and lump coal rate to optimize and analyze the traction speed of shearer, and the optimized cutting specific energy consumption, production efficiency and lump coal rate were significantly improved.

1.3 Research on drum load

In 2010, Su [16] used discrete element analysis method to simulate the cutting process of rock and came to the conclusion that the cutting load value of the average pick was similar to the test result. In the same year, Dinescu [17] studied the influence of different factors of shearer on traction speed. The relation between load and traction speed of different coal strength and different wear degree of cutting head is obtained; In 2011, Ebrahimabadi [18] studied the cutting performance of shearer and obtained the prediction model of cutting performance through statistical analysis; In 2013, MiKl [19] simulated the cutting process of the pick through ABAQUS and obtained the load of the pick with different structures; In 2017, Chen [20] used mathematical statistics to obtain the mean and standard deviation of shearer drum's triaxial force under different traction speeds, and finally verified the correctness of the theoretical model through experiments; In the same year, Li [21] established a mathematical model for the mean value of shearer drum load, and analyzed and obtained the curve of the mean value of drum load changing with the traction speed; In 2021, Ma [22] used MATLAB to conduct simulation analysis on the load of drum under different traction speeds of the shearer, and obtained the law that the traction speed is proportional to the load of the drum.

The above scholars have done a good job in the analysis of ordinary coal or rock or coal containing gangue, but relative study about cutting coal with hard concretion is rare. If the actual working conditions can be simulated by discrete element simulation, and take the cutting specific energy consumption of the drum, coal loading rate, and load as the research content, explore the influence of shearer traction speed on the drum load, coal loading rate and cutting specific energy consumption. The load, coal loading rate and cutting specific energy consumption of coal containing hard concretion were considered comprehensively, the comprehensive index is established, and the traction speed is optimized, so as to obtain the optimal kinematic parameters of the cutting drum for cutting hard concretion. This will provide better practical significance and engineering application value for improving the working efficiency of shearer and improving the cutting energy consumption of drum.

2 Sampling and mechanical properties test

According to the underground survey, the thickness of coal seam at the target working face is 0.8–1.1 m, and the coal seam is dominated by bright-banded coal. The average exposed density of iron sulfide hard concretion in the coal seam is 0.1405 m, located at the height of 0.275 m, and the elliptic dimension is about 200 mm × 100 mm, as shown in Figure 1.

The coal and hard concretion in the target mining area are cut, and the samples are shown in Figure 2a, and conduct standardized tests to obtain their mechanical properties. The testing process is shown in Figures 2b–2e, relevant parameters are listed in Table 1.

3 Establishment of discrete element model

3.1 Configuration of parallel bond

The contact types between coal particles and hard concretion particles are set as Hertz-mindlin with bonding. The contact type between hard concretion coal particles and shears drum model are set as Hertz-Mindlin (no slip).

In discrete element simulation, the generation of regular ellipsoidal hard concretion and the correct setting of the bonding parameters between hard concretion and coal are important factors affecting the drum load, cutting specific energy consumption and coal loading rate, and are also the premise of reliable simulation. In order to solve the bonding problem between coal and hard concretion particles, it is necessary to calculate the normal stiffness per unit area K_n, shear stiffness per unit area K_s, critical normal stress σ, critical shear stress $\tau$and bonded disk radius r; The bonding parameters of coal and hard concretion particles are obtained [23].

Fig. 1. Underground coal seam condition.

Based on Hertz contact theory and Mindlin's scientific research results, K_n and K_s of particles are obtained by formula (1).

$$\begin{cases} K_n = \dfrac{4}{3}\left[\dfrac{(1-v_1{}^2)}{10^9 E_1} + \dfrac{(1-v_2{}^2)}{10^9 E_2}\right]^{-1}\left[\dfrac{r_1+r_2}{r_1 r_2}\right]^{0.5} \\ K_s = \dfrac{2K_n}{3} \end{cases}. \quad (1)$$

In Formula (1), K_n is the normal stiffness per unit area, N/m; K_s is shear stiffness per unit area, N/m; v_1 and v_2 are Poisson's ratio of coal and hard concretion particles; E_1 and E_2 are the elastic modulus of two kind of particles, MPa; r_1, r_2 are the radius of the two particles, mm.

Based on Mohr-Coulomb theory, the value of σ and τ can be calculated, as shown in formula (2).

$$\begin{cases} \sigma = 0.5(\sigma_1+\sigma_3) + 0.5(\sigma_1-\sigma_3)\cos(2\alpha) \\ \tau = C + \sigma \tan\phi \\ \alpha = 45 + \dfrac{\phi}{2} \end{cases}. \quad (2)$$

In Formula (2), σ is critical normal stress, MPa; τ is critical shear stress, MPa; σ_1 is the maximum stress, MPa; σ_3 is the minimum stress, MPa; α is shear failure angle, °ϕ is the internal friction angle, °; C is the cohesion of coal and concretion, MPa. In the formula, σ_1 and σ_3 can be calculated by the modified Griffith formula, as shown in Formula (3).

$$\begin{cases} \sigma_3 = -\dfrac{\sigma_c\left[(1+\mu^2)^{0.5}-\mu\right]}{2\mu} \\ \sigma_1 = \dfrac{\left[\sigma_3\left((1+\mu^2)^{0.5}+\mu\right)-4\sigma_t\right]}{\left[(1+\mu^2)^{0.5}-\mu\right]} \end{cases}. \quad (3)$$

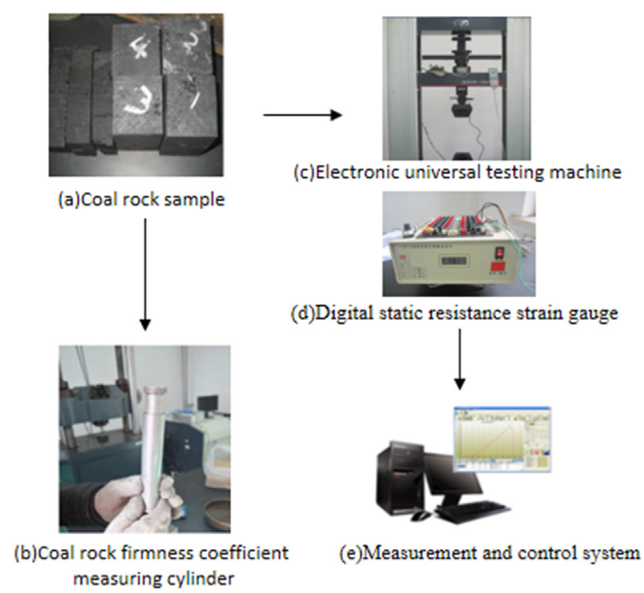


Fig. 2. Testing process of mechanical properties.

In Formula (3), σ_t is the tensile strength of the material, MPa; σ_c is the compressive strength of the material, MPa; μ is the coefficient of friction between material cracks.

Table 2 shows the parallel bonding parameters obtained by substituting relevant coal and concretion mechanical properties parameters in Table 1 into formulas (1)–(3).

According to the actual underground sampling situation, the bonded disk radius between hard concretion particles are set as 7 mm, between coal particles are set as 12 mm, between hard concretion particle and coal particle are set as 13 mm. The cohesive force parameters set between coal and rock particles are shown in Figure 3 [24].

Table 1. Mechanical properties.

Coal and hard concretion	Coal	Hard concretion
$(\mathrm{kg \cdot m^3})\rho$	1417	2963
Poisson's ratio ν	0.28	0.18
(MPa)E	2000	15000
(mm)r	12	7
(MPa)σ_t	0.66	8.31
(MPa)σ_c	5.23	83.94
(MPa)C	0.81	11.52
$(^\circ)\phi$	52	48
Coefficient of firmness f	1.4	8.4

Table 2. Setting of adhesion parameters between particles.

Contact type	$K_n/(\mathrm{N/m})$	$K_s/(\mathrm{N/m})$	σ/MPa	τ/MPa
Coal and coal	1.02×10^8	6.82×10^7	5262	7544
Between hard concretions	5.17×10^8	3.44×10^8	1138	1379
Coal and hard concretion	1.47×10^8	9.77×10^7	5216	6833

And the friction coefficients between particles are set as shown in Table 3 [25].

3.2 Filling of coal wall particles containing hard concretion

3.2.1 The shape of coal wall space

According to the distribution of coal seam in mining face and the data of hard concretion measured underground, the overall size of hard concretion is set as 200 mm × 100 mm × 100 mm, and the simulated coal wall space is established, as shown in Figure 4.

In order to reduce the gap between particles and improve the filling efficiency of particles, and make them contact fully. The generation space of coal wall particles is divided into five geometric bodies from top to bottom: top coal space I, hard concretion space II, middle coal space III, bottom coal space IV and coal wall space shell V. The coal wall space model is imported into EDEM in STL format, and hard concretion and coal particles are generated according to the regions divided in coal wall space layer by layer.

3.2.2 Establishment of hard concretion bodies

The particle type is defined as hard concretion, the step size is set as 20%, the particle grid is set to 2Rmin, and the dynamic particle generation mode is selected to fill the space II of hard concretion. The establishment of hard concretion is completed after particles stabilization, as shown in Figure 5.

3.2.3 The establishment of coal wall

Select the generating space of coal particles, define the particle type as coal, and generate particles by static filling method. After the coal and hard concretion particles are stabilized, the hard concretion space II and the coal space I, III and IV are deleted, which make the coal and hard concretion fully contact. According to the data in Table 2, the bonding parameters are introduced into EDEM software, and the bonding time is set to make the particles fully bonded. When all particles tend to be stable, the coal wall space shell V is deleted to complete the establishment of the discrete element model of coal wall with hard concretion, as shown in Figure 6.

3.3 Establishment of mechanical model

Based on UG, through rotation, symmetrical stretching command, the pick contour model is achieved and drag it into reuse library. Through the component family command, select the pick model, input the rotation angle, installation angle and other information in Table 4 into the spreadsheet to generate the pick family table. Based on shell extraction, spiral line, sweep command to complete

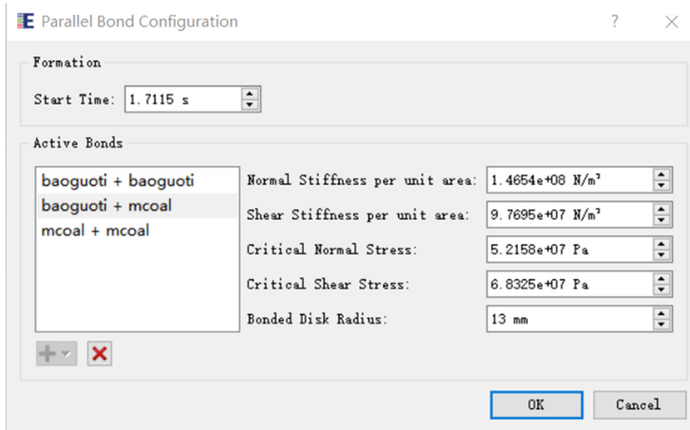


Fig. 3. Parallel bond configuration between hard concretion and coal.

Table 3. Friction coefficient between particles.

Particles	Coefficient of dynamic friction	Coefficient of static friction	Coefficient of recovery
Coal and coal	0.035	0.75	0.62
Between hard concretions	0.02	0.55	0.56
Coal and hard concretion	0.05	0.55	0.5

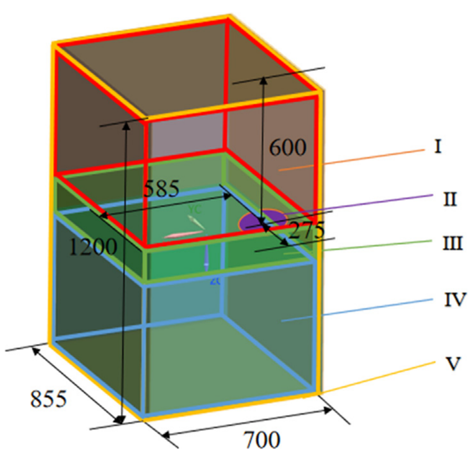


Fig. 4. Spatial distribution of coal wall.

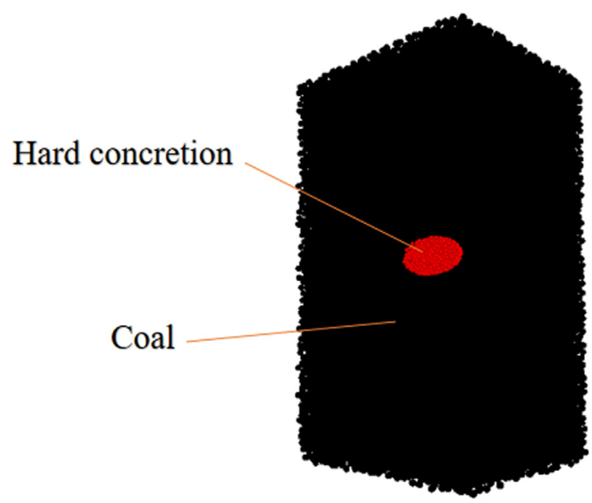


Fig. 6. Coal wall model.

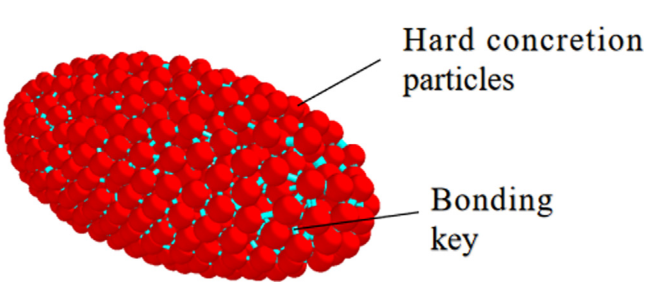


Fig. 5. Hard concretion model.

the establishment of the basic drum body. Enter the installation information of each pick in the reuse library and drag it to the assembly area to complete the assembly with the basic drum body, as shown in Figure 7.

Based on the cutting state given by the shearer project, adjust the rocker arm angle and assemble the drum at the outstretched end of the rocker arm, import it into EDEM in STL format, unit set mm, and the complete EDEM model is shown in Figure 8.

By adding kinematics parameter command, set the traction speed of the shear and rotation speed of drum, set the drum and picks' rotation motion type as follow-up to ensure that the axis and motion direction are consistent with the cutting direction, and complete the kinematic parameter setting of the mechanical model.

Table 4. Installation parameters of picks.

Cutting line	Number of picks	Rotation angle (°)	Installation angle (°)	Radius (mm)
A	4	–47	70	392
B	2	–35	70	392
C	2	–20	70	398
D	1	–12	70	398
E	1	0	0	400
1	2	0	0	400
2	2	0	0	400
3	2	0	0	400
4	2	0	0	400
5	2	0	0	400
6	2	0	0	400
7	2	0	0	400

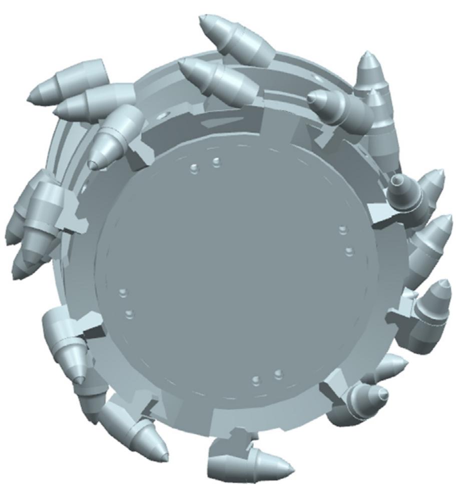


Fig. 7. Drum model.

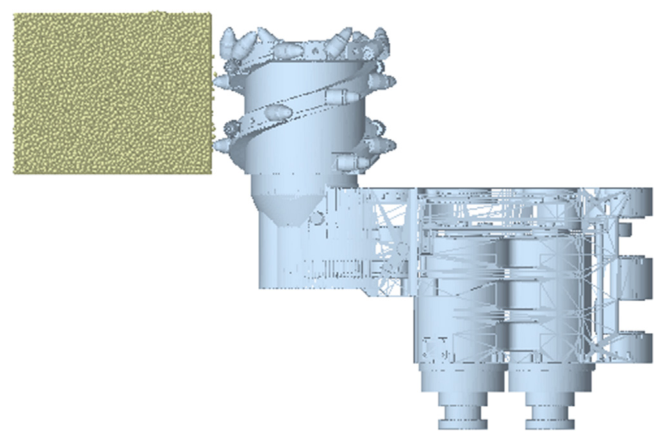


Fig. 8. EDEM model.

4 Discrete element simulation

4.1 Cutting load analysis of spiral drum

Taking MG2×70/325-BWD shearer as example, the rotational speed of cutting motor is 1462 r/min, the transmission ratio is 16.86, so the drum speed is constant value 86.7 r/min. A variable-frequency motor is used in traction unit, the loaded traction speed range is 3–6 m/min. Taking the traction speed 4 m/min and drum speed 86.7 r/min as condition, the loading process of drum cutting hard concretion is simulated. The drum of shears has experienced the process of cutting coal, impacting hard concretion, cutting the hard concretion off, peeling hard concretion out of coal successively. These 4 steps are shown in Figure 9a–d, respectively.

After the simulation solution is completed, the three-axis force, torque of the drum model are selected for post-processing and the results are output, as shown in Figure 10. 0–4.9 seconds is the drum load curve during coal cutting, as shown in Figure 10a, as the pick cuts up homogeneous coal particles, the whole load curve fluctuates evenly, and the maximum load is 27501.8641N; 4.9–5.21 s is the drum load curve when the drum cutting hard concretion, the impact load of the pick reaches the first peak value 74014.4463N, just because the medium changes suddenly from coal to hard concretion. Even greater force is required to break the parallel bond between coal and hard concretion. Of course, due to the different traction speeds, the action positions of the picks and the hard concretion are also different, and this process has certain randomness, which cases the peak loads are greatly different. In order to clearly describe the influence of traction speed on drum peak load, high-dimensional fitting is more appropriate. After the load reaches peak value and then decreases rapidly, this phenomenon is caused by the hard concretion pressed into the coal, as the parallel bond of the coal wall is weaker than the hard concretion, the coal parallel bond will break first, which leads to the picks and hard concretion have a common displacement, the hard concretion can't be cut further and the load drops sharply and fluctuates within a certain range; The drum continues to move at the given traction speed and speed, at 5.21 s, the energy provided by the drum is breaks the hard concretion and

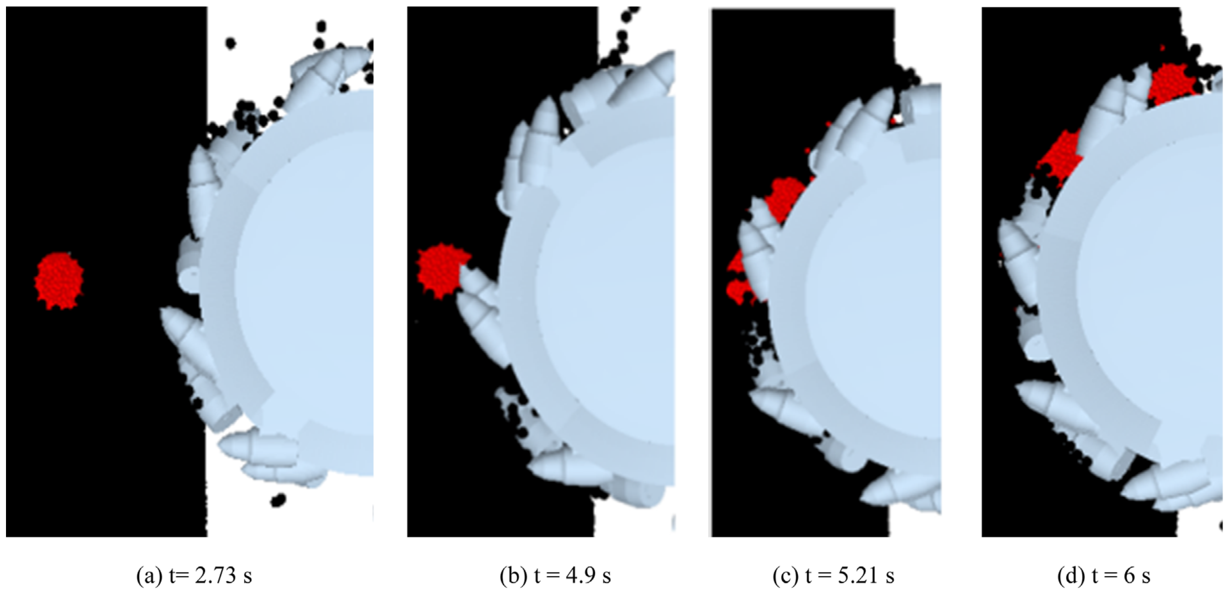


Fig. 9. Simulation process of hard concretion cutting.

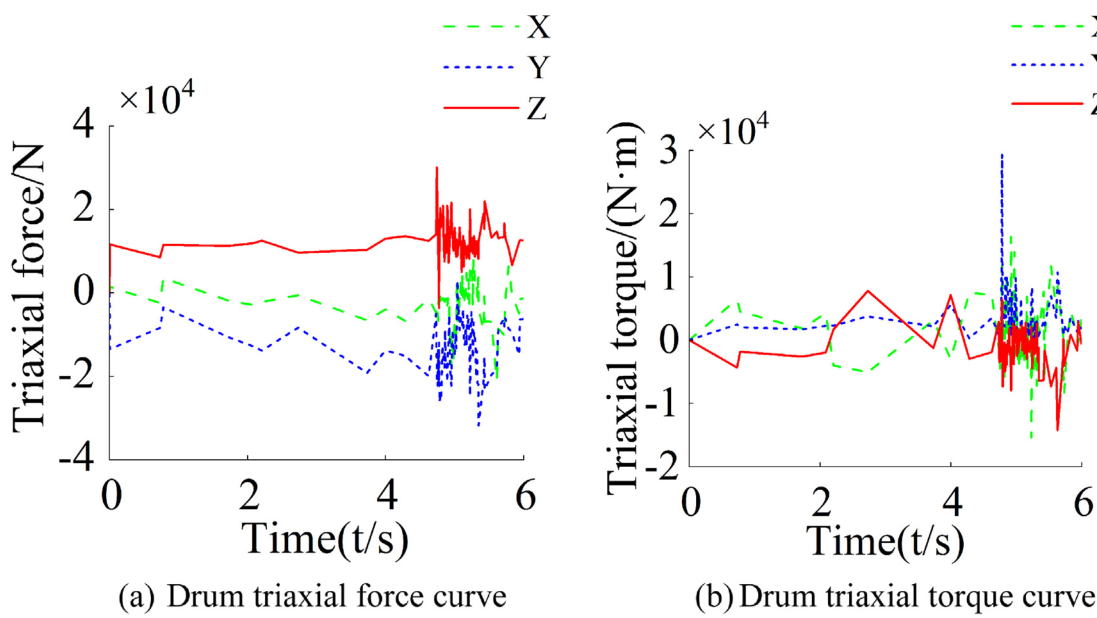


Fig. 10. Instantaneous load curves of the drum.

destroys its bond, but at this time, the coal also bears part of its energy, so its load reaches the secondary peak value, which is much smaller than the first peak and the hard concretion is stripped. Several picks collide with the concretion body successively, forming complex time-varying and nonlinear dynamic load characteristics, and the peak load is 25436.1486N at this time. In 5.21–6 seconds, the hard concretion is peeled off, and the drum resumes to the coal cutting stage, and the load changes are relatively stable.

Finally, through multiple groups of simulation output results, it is found that under the working conditions of constant speed and traction speed of 3–6 m/min, the laws of triaxial force and torque of shearer cutting hard concretions are basically consistent, as shown in Figure 10b, but the peak loads under different working conditions are different, as shown in Table 5.

4.2 Influence of traction speed on cutting specific energy consumption

Cutting specific energy consumption H_w refers to the energy consumed by the drum in cutting unit volume of coal, and its expression is shown in Formula (4).

$$H_w = \frac{M_s n}{9550BHv}. \tag{4}$$

Table 5. Installation parameters of picks.

Traction speed / (m/min)	Cutting specific energy consumption / (kW · h/m^3)	Coal loading rate / (%)	Peak load / (kN)
3	1.779	37.812	63.324
4	1.504	34.580	74.014
5	1.296	32.214	69.478
6	1.164	30.931	92.147

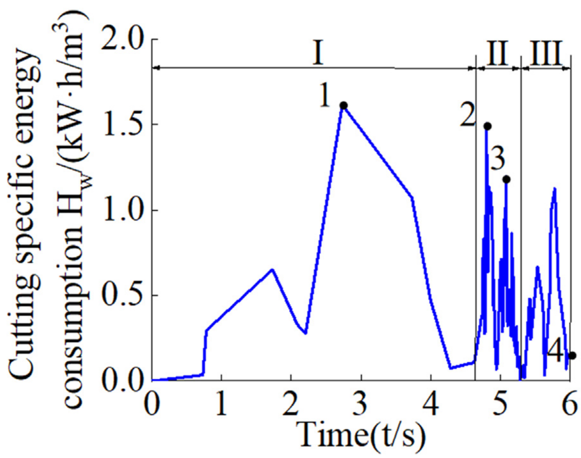


Fig. 11. Cutting specific energy consumption curve.

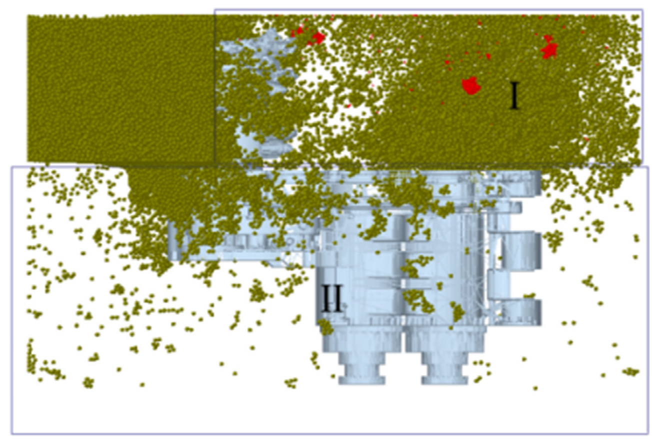


Fig. 12. Division of model area.

In the Formula: H_w is the cutting specific energy consumption of shearer drum, kW · h/m^3; M_s is the total cutting resistance torque, N · m; H is the drum mining height, m; B is the cutting depth of drum, m; v is the traction speed of shearer, m/min; n is the drum rotation speed, r/s.

Bring the cutting resistance torque obtained by simulation shown in Figure 10b into formula (4), and the cutting specific energy consumption curve can be obtained, as shown in Figure 11.

4.2.1 Coal cutting stage I

According to the cutting specific energy consumption formula (4), when the drum speed, traction speed and cutting depth are constant, the cutting specific energy consumption is mainly determined by the cutting resistance torque and mining height. From 0 s to 4.9 s, as the drum continuously cuts into the coal wall, the number of picks contacting to the coal wall also increases. The total cutting torque of the overall drum increases sharply, as shown in Figure 10b, but the mining height increases steadily, so when the drum reaches point 1 (time: 2.72 s), the picks are fully in contact with the coal, the cutting specific energy consumption reaches the maximum value 1.616 kW · h/m^3. The cutting effect is shown in Figure 9a. As the drum continues to cut into the coal wall, the mining height is basically constant, and the fluctuation of cutting specific energy consumption is basically consistent with the change trend of cutting resistance torque. As shown in Figure 10b, the torque drops after reaching a peak, so the cutting specific energy consumption also drops significantly as shown in Figure 11.

4.2.2 Hard concretion cutting stage II

Within 4.9–5.2 s, the pick contacts hard concretion, according to Bielong's dense core theory, when the pick contacts the hard block, a non-linear sudden load will be generated. The law of specific energy consumption for cutting is similar to the law of peak load change, and the law is also non-linear, that is, the drum reaches point 2, ushering in the first sudden change of drum cut hard concretion. At this time, the cutting specific energy consumption is 1.504 kW · h/m^3, as shown in Figure 9b. At 5.21 s, the hard concretion is peeled off, the energy of hard concretion pressed into the coal wall is released, and the resistance torque increases again, but its amplitude is less than the first sudden change value. Therefore, when the drum reaches the position point 3, it undergo the second shocking load, the cutting specific energy consumption reaches peak again, and the cutting specific energy consumption is 1.134 kW · h/m^3. After hard concretion cut off from coal seam, the cutting energy consumption gradually decreased until the completion of hard concretion resection. The cutting effect is shown in Figure 9c.

4.2.3 Hard concretion peeling stage III

In 5.2–6 s, the drum is almost completely in contact with the coal wall, the load on the drum decreases slowly with

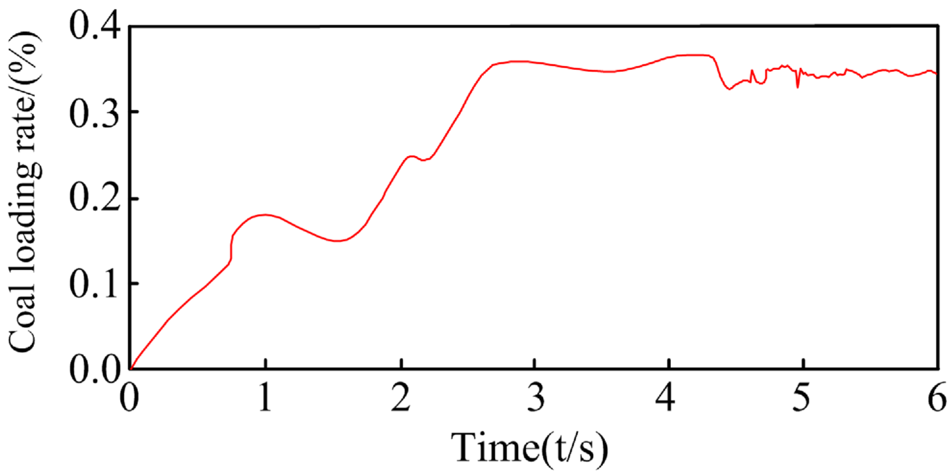


Fig. 13. Coal loading rate.

time, the cutting specific energy consumption begins to drop sharply, and hard concretion are transported out of the coal with the movement of the drum blade. That is, when the drum reaches point 4, hard concretion are thrown out as shown in Figure 9d.

4.3 Analysis of coal loading rate

Low coal loading rate of shearer for thin coal seam is a common problem in mining process. In order to explore the influence rule of traction speed on coal loading rate, two statistical regions are established in EDEM: Statistical area I is the volume of coal and hard concretion particles not falling on the scraper conveyor, and statistical area II is the volume of coal and hard concretion particles falling on the scraper conveyor, as shown in Figure 12. The calculation formula of the coal loading rate is shown in Formula (5):

$$\eta = V_2/(V_1 + V_2). \tag{5}$$

In Formula (5): V_1 is the volume of particles in area I, m^3; V_2 is the volume of particles in area II, m^3.

The curve of coal loading rate calculated by Formula (5) is shown in Figure 13. With the contact between the pick and coal, some particles begin to appear in the coal loading area, and the coal loading rate increases gradually. After 2.8 s, the drum is in full contact with the coal, and a large number of particles are thrown out and accumulated in the coal loading area. At 4.9 s, the drum cut hard concretion. As few coal particles are detected in the statistical area, the coal loading rate decreased temporarily. When hard concretion is peeling off, the coal loading tends to be stable. In this process, the maximum coal loading rate is 36.67%, and the average coal loading rate after stabilization is 34.58%.

4.4 Analysis of traction speed on comprehensive performance of drum

In order to analyze the influence of traction speed on comprehensive cutting performance of the drum, considering that the set range of traction speed of shearer in thin coal seam is 3–6 m/min, the simulated traction speeds are set as 3 m/min, 4 m/min, 5 m/min and 6 m/min respectively, after analyzing the above working conditions with EDEM, the maximum peak load, the cutting specific energy consumption of the pick collides hard concretion for the first time, the average coal loading rate are obtained as shown in Table 5.

According to the cutting specific energy consumption formula (4), the function relationship between the hauling speed of shearer and the cutting specific energy consumption is monotone and nonlinear decreasing. 2 order of the fitting function will be selected. According to the coal loading rate formula (5), In the actual coal mining operation, the growth rate of V_1 is higher than that of V_2, so the loading rate of the shearer will generally decrease with the increase of the traction speed, and the relationship is approximately linear. 1 order of the fitting function will be selected. When drum cutting hard concretion at different traction speeds, the energy carried by the picks and the action position on the hard concretion are different. So the loads are greatly difference, it is nonlinear, for 4 data points, 3 order of the fitting function will be better.

The simulation data is analyzed by origin software, the fitting curves and the corresponding errors will be automatically drawn and calculated after entering the order of the fitting functions. The root mean square error calculate method as shown in formula (6), when the cutting specific energy consumption curve use 2 order fitting function, the minimum error is 8.0534×10^{-4}; when the coal loading rate curve use linear fitting function, the minimum error is 9.2269×10^{-5}; when the load peak of cutting hard concretion use 3 order fitting function, the minimum error is 0, the fitting curve is shown in Figure 14.

$$e_{MSE} = |\sum_{i=1}^{n}(x_i - x_i^*)^2|. \tag{6}$$

In Formula (6): x_i is the value of the ith data point; x_i^* is the value of the ith point of the fitting function; n is total number of data points.

Figure 14 is the fitting curves of cutting specific energy consumption, drum load and coal loading rate, it can be seen from Figure 14 that the load on the drum increases

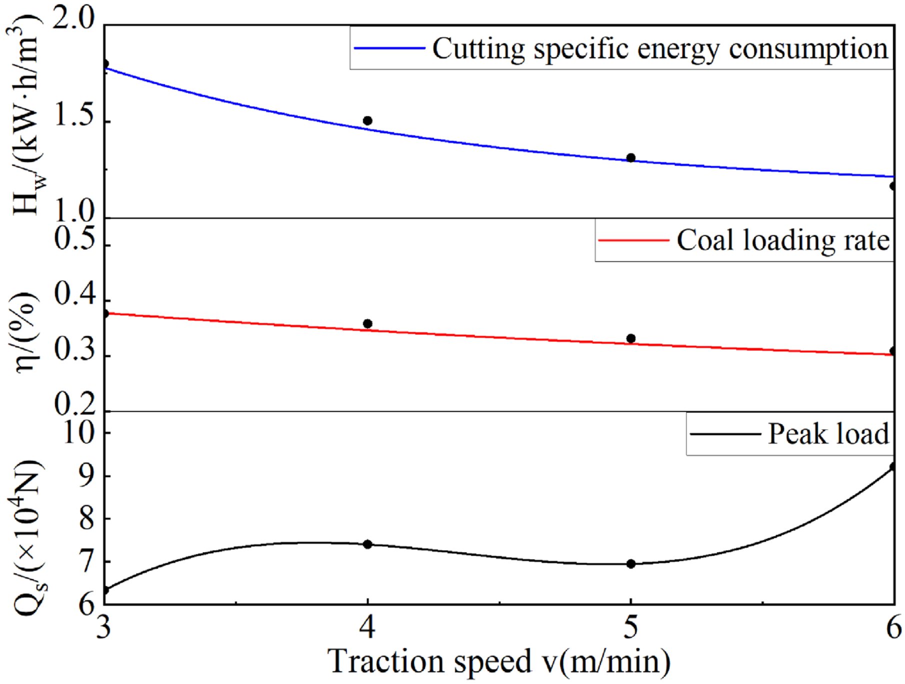


Fig. 14. Fitting curves of cutting specific energy consumption, drum load and coal loading rate.

first, then decreases and then increases with the increase of traction speed. The setting of lower traction speed will increase the specific energy consumption of shearer drum for cutting the coal containing hard concretion, resulting in excessive waste of energy. The setting of higher traction speed will reduce the energy consumption of the shearer, but it will increase the force on the drum and reduce the loading rate of the shearer, thereby affecting the cutting efficiency of the drum. The coal loading rate and cutting specific energy consumption of drum decrease with the increase of traction speed. The fitting relation function of traction speed v to cutting specific energy consumption, drum load and coal loading rate is obtained by fitting with Matlab toolbox, as shown in Formula (7).

$$\begin{cases} Q_s = -48.441 + 39.636v - 9.248v + 0.707v \\ \eta = 0.448 - 0.025v \\ H_w = 3.34 - 0.702v + 0.059v \end{cases}. \quad (7)$$

In the formula: Q_s is the maximum load of the drum, N; η is coal loading rate, %; H_w is cutting specific energy consumption, $\mathrm{kW\cdot h/m^3}$.

5 Traction speed optimization

5.1 Objective function

In order to make the comprehensive performance of thin coal seam shearer better, the maximum coal loading rate η and minimum drum load Q_s and specific energy consumption H_w are taken as multi-objective optimization functions. That is:

$$\min[1-\eta, Q_s/Q_{s\,\max}, H_w/H_{w\,\max}].$$

Considering the weight of each factor, the multi-objective optimization is transformed into single objective optimization for solution, then the transformed objective function is:

$$minF(x) = min\left[\lambda_1(1-\eta) + \lambda_2(Q_s/Q_{s\max}) + \lambda_3\frac{H_w}{H_{w\,\max}}\right].$$

In the Formula, λ_1, λ_2 and λ_3 are the weight coefficients respectively, which are set as 0.5, 0.2 and 0.3 according to the production needs of thin coal seam shearer. $Q_{s\,\max}$ is the maximum load of the drum, N; H_w is the maximum cutting specific energy consumption in the discussion domain, $\mathrm{kW\cdot h/m^3}$.

5.2 Design variables

Taking the traction speed of thin coal seam shearer as the design variable:

$$X = [v_q]^T = [x_1]^T.$$

5.3 Constraints

5.3.1 Value range of traction speed:

$$g_2(X) = x_1 - 6 \le 0$$

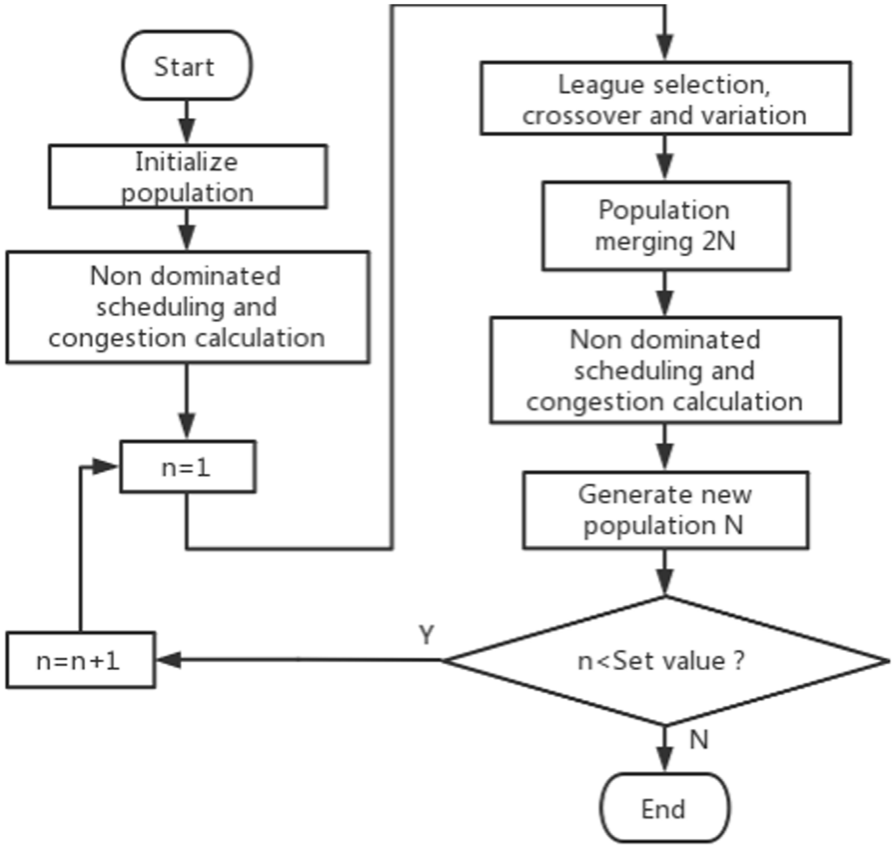


Fig. 15. Flow chart of NSGA-II algorithm.

$$g_1(X) = 3 - x_1 \leq 0$$

5.3.2 Limit of cutting power

$$g_3(X) = \frac{60M_s n}{9550} - \gamma P_0 < 0.$$

In the formula, γ is the transfer efficiency of mechanical system; P_0 is the power of cutting motor, kW.

5.4 Optimization solution

For the above constrained multi-objective optimization problem, NSGA-II algorithm is used to solve the objective function [26]. NSGA-II algorithm flow chart is shown in Figure 15.

Multi-objective optimization is carried out by NSGA-II algorithm. With traction speed as constraint condition, coal loading rate, drum load and cutting specific energy consumption as objective function, the population number is set as 1000, the number of evolution is set as 5000, crossover probability is 85% and mutation probability is set as 15%, and perform iterative calculation. The result of iteration is shown in Figure 16.

The optimal solution of the optimization equation is $x_1 = 3.53$, that means when the drum speed and traction speed are 86.7 r/min and 3.53 m/min, the drum reaches the optimal cutting, and the coal loading rate is 32.2%. The peak load of shearer drum is 69239.56 N; The cutting specific energy consumption is 1.301 $\mathrm{kW \cdot h/m^3}$.

6 Experimental Verification

The triaxial force sensor is installed between the output shaft of the planetary reducer and the drum of the cutting unit of the shearer, and the triaxial force signal transmission and wire winding problems are solved by using conductive slip ring. By adjusting the traction motor frequency, the average traction speed of the shearer reaches 3.53 m/min. The working state of the shearer in the target mining area is shown in Figures 17a, 17b As shown in Figure 17c, the collected triaxial force data is transmitted to the upper computer for processing and analysis, and the triaxial force curve is obtained, as shown in Figure 18a. At 0–1.65 min, the average load of the shearer is 26.91 kN; At 1.65-1.656 min, the shearer cuts hard concretion, and at 1.652 min, a high-frequency impact is produced, and the peak load is 66.05 kN; At 1.656–2 min, the hard concretion are stripped out and the shearer resumes the coal cutting stage. Figure 18b is partial enlarged view of the load curve

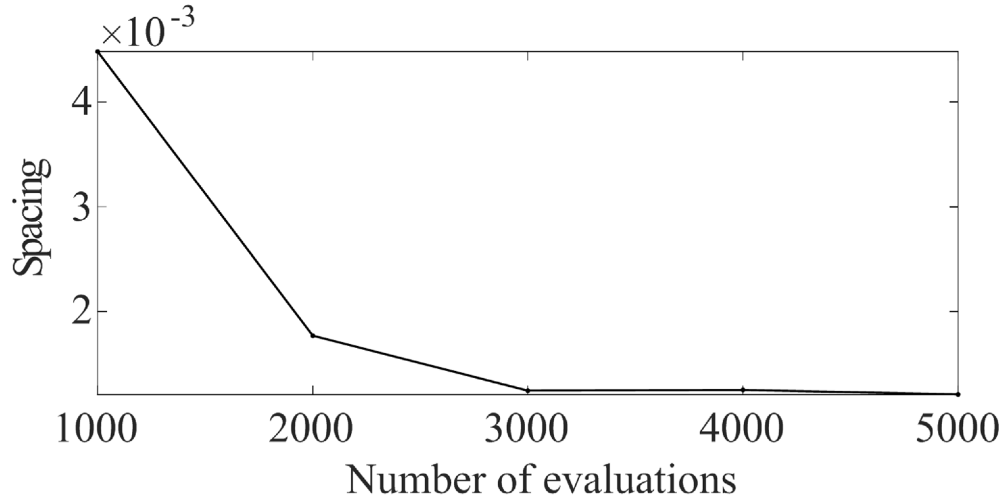
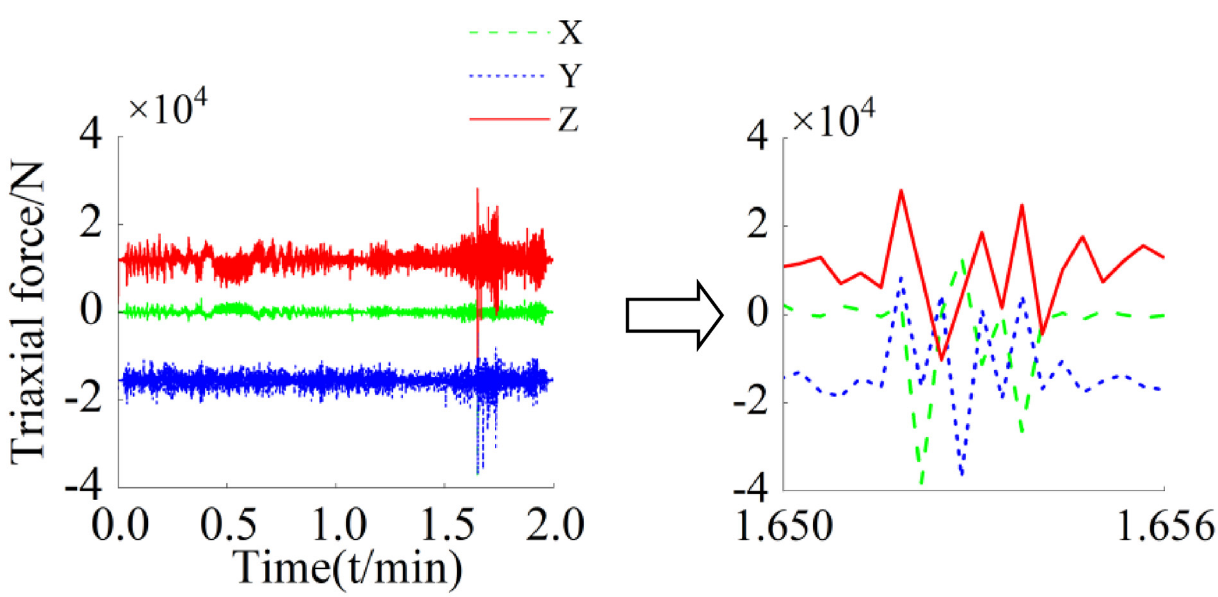


Fig. 16. Iterative convergence diagram.

(a) Maximum haulage speed (b) Working in coal mine (c) Analysis of measured signals

Fig. 17. Actual underground cutting condition and signal processing.



(a) Triaxial force curve (b) Partial enlarged force curve

Fig. 18. Load curve of spiral drum.

when the drum cuts hard concretion. It can be seen from Figure 18b that there are four large shocks in the process of cutting hard concretion. Based on the dense core theory of coal breaking theory [27] and the experimental analysis results, it is basically consistent with the law of cutting hard concretion in the simulation curve (Fig. 10), and the maximum error rate of its load does not exceed 4.46%, which proves that the research and application method of using EDEM to analyze the instantaneous load simulation of shearer drum is reliable.

7 Conclusion

Taking a thin coal seam shearer as the prototype, the mechanical model of shearer cutting section is established by UG, which is imported into EDEM in STL format. The parallel bonding of coal and hard concretion particles are configured, and the discrete element model of shearer cutting coal wall containing hard concretion is built. The influence of traction speed on cutting load, cutting specific energy consumption and coal loading rate is analyzed by simulation, and verified by experiments. The main conclusions are as follows:

- Shearer traction speed has a cubic curve relationship with the load of the drum, a linear relationship with the coal loading rate of the drum, and a quadratic curve relationship with the cutting specific energy consumption, and the fitting function of traction speed and cutting specific energy consumption, drum load and coal loading rate are established.
- Taking coal loading rate, drum load and cutting specific energy consumption as objective functions, a multi-objective optimization equation of shearer drum kinematics parameters is established. The optimal value of traction speed is obtained through optimization, that is, the traction speed is $3.53\mathrm{m/min}$ and the cutting specific energy consumption is $1.301\mathrm{kW \cdot h/m^3}$. Coal loading rate is 32.2%; The peak load of the drum is 69239.56 N.
- The instantaneous triaxial force and torque curves of the drum are obtained by simulation, and compared with the triaxial force and torque curve obtained by experiment, the maximum error rate of shearer drum load is not more than 4.46%. The accuracy and feasibility of discrete element simulation are proved.

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