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Study on working performance of multi-impact drum

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Abstract: The current depletion of high-quality coal seams, hard coal mining had become the norm, while the traditional mechanical cutting methods were inefficient. A multi-impact cutting technology was proposed, which was to design a hydraulic system inside the drum. A hydraulic control system was formed by the hydraulic impact pick driver set by the ranging arm and the cutting motor to realize the reciprocating impact movement of multiple picks. The impact of picks was used to make the coal synchronously pre-crack, thereby reducing the difficulty of hard seam mining. In this paper, by analyzing the working process of the multi-impact drum, the corresponding mechanical model was established and the overall research plan was determined. A simplified drum model was established using CATIA, a coal model was established in EDEM based on the physical and mechanical properties of hard coal, and a simulation experiment composed of the cutting drum and coal model was based on orthogonality. The test method explored the working performance of the multi-impact drum under the action of multiple factors in cutting different media, using different impact frequencies and different drum speeds. The results showed that the coal breaking rate was used as the evaluation index, the order of the influencing factors was: A>C>B (coal hardness> drum speed> impact frequency), and the optimal plan combination was A2B1C3 (coal wall hardness was f5, impact frequency was 4Hz, drum speed was 40\textcdot\text{min}^{-1}); taking cutting specific energy consumption as the evaluation index, the order of influencing factors was: C>A>B (drum speed>coal hardness>impact frequency), the optimal plan combination was A2B1C3 (coal wall hardness was f5, impact frequency was 4Hz, drum speed was 40\textcdot\text{min}^{-1}). The matrix analysis method was further introduced to calculate that the order of the influence of each factor on the index value of the orthogonal test was C>A>B (drum speed>coal hardness>impact frequency), when the coal hardness was f5, the impact frequency was 4Hz, and the drum speed was 40\textcdot\text{min}^{-1}, the working performance of the multi-impact cutting drum was the best. Under the same working conditions (coal hardness was f5, drum speed was 40\textcdot\text{min}^{-1}), a comparative simulation experiment of the traditional drum was carried out. Compared with the simulation results, the coal falling amount of the multi-impact drum was about 24.86\% higher than that of the traditional drum, and the cutting specific energy consumption of the multi-impact...
drum was 0.7423 kW-h/m², which was about 21.67% lower than that of the traditional drum. Finally, a simplified multi-impact drum industrial cutting test was carried out. The test results showed that the cutting resistance of the multi-impact drum was about 17.22% lower than when there was no impact. Considering that the simplified multi-impact cutting drum had a reduced impact pre-cracking effect on the coal, it can be considered that the results of the industrial test and the discrete element simulation test were still relatively consistent. The multi-impact cutting drum had good working performance under hard coal conditions.

**Keywords:** Multi-impact drum • Hard coal • Discrete element • Orthogonal test • Matrix analysis

1 Introduction

The long-term large-scale mining has led to a rapid decline in the reserves of high-quality coal. The mining work with complex conditions such as thin seam [1], hard seam [2], gangue seam [3], and high gas seam [4] is inevitable. However, traditional cutting methods can no longer achieve the desired results under complex seam, restricting mining efficiency and becoming one of the main reasons for the gradual decline in annual coal production in recent years.

The reduction in mining efficiency of traditional cutting methods under complex conditions is caused by multiple factors. The special occurrence conditions of complex seam are often not single, such as hard thin seam, gangue thin seam, high gas hard seam, etc. In these cases, it is difficult to achieve good results by changing the size or power of the cutting mechanism, because the internal structure of complex seam determines the difference in mechanical properties compared with high-quality seam, thereby reducing the applicability of the coal breaking mechanism of traditional cutting methods. Therefore, study on new cutting methods for complex conditions is an important scientific orientation of the current coal industry.

In recent years, there are a wide variety of new coal-breaking technologies, which are classified according to their working principles and can be divided into jet cutting [5-7], jet-assisted mechanical cutting [8-11], special-shaped pick cutting [12-14], laser cutting [15-18], drilling expansion agent cutting [19-20]. Compared with traditional mechanical cutting methods, the mining efficiency of the above methods under different conditions is improved, but they also have certain limitations from a general perspective. For example, the water jet may increase the viscosity of coal and the abrasive jet may cause the abrasive particles to be mixed into the coal, which increases the difficulty of subsequent coal washing and coal preparation; the processing cost of special-shaped pick is higher, and there are higher requirements in its material strength; laser cutting is not easy to control the energy range, and it may change the properties of coal, which will lead to physical failure; the process of drilling expansion and cracking agent is more complicated and the construction time is long. Therefore, a multi-impact cutting technology is proposed by author, which is to design a hydraulic system inside the drum. A hydraulic control system is formed by the hydraulic impact pick driver set by the ranging arm and the cutting motor to realize the reciprocating impact movement of multiple picks. The impact of picks is used to make the coal synchronously pre-crack, thereby reducing the difficulty of hard coal mining. The article will focus on the work performance of the multi-impact drum, by constructing a mechanical model of multi-impact cutting, analyze the factors affecting coal efficiency and work performance evaluation indexes, and combine numerical simulation and industrial test verification methods to explore the working performance of multi-impact drum under hard seam.

2 Analysis of the Structure and Mechanical Model of the Multi-impact Drum

2.1 Structure of Multi-impact Drum

The multi-impact drum is modified based on the structure of the traditional drum. As shown in Figures 1 and 2, the hydraulic control system is installed inside the drum, and the ranging arm and motor are equipped with hydraulic pressure. The impact pick drive and its pipes are connected to the shearer hydraulic oil tank, the pipes of drive are connected with the pipes of drum and the pipes of picks, which are used to control multi-impact drum. All the picks above are hydraulic impact picks. Through the same hydraulic control system, multiple hydraulic impact picks are controlled to impact or retract, so that the hydraulic impact picks on the entire drum alternately impact coal. Before cutting the surface of the seam, a certain depth of impact hole can be quickly provided in the pre-contact area to form a local unloading area to achieve the purpose of unloading the overall coal and rock. It has the same rotary cutting as the normal drum while impact unloading ability.
Figure 1  Structure of the multi-impact drum

Figure 2  Distribution with pipe of the multi-impact drum

The schematic diagram of the impact pick drive control system is shown in Figure 3. The drive system consists of motor, hydraulic pump, replenishing pump, and tank, the impact picks, two hydraulic circuits, frame, control device, two pressure sensors, five solenoid valves, two flow sensors, filters, accumulators, liquid circuit heat exchangers and two temperature sensors. As shown in the figure, the motor, hydraulic pump, and replenishing pump are installed on the same frame. The fluid tank is responsible for supplying hydraulic oil to the replenishing pump. The replenishing pump is responsible for delivering the hydraulic oil to the hydraulic pump. The hydraulic pump is connected to the hydraulic circuits, which is to supply liquid to impact picks that need to perform impact motion for driving. The inverter drive system inputs the pressure, temperature, and flow data to the control device through the pressure sensor and other signals, and then outputs a series of signals to the solenoid valve for corresponding movement to achieve stable and reliable internal operation of the drive system.

Figure 3  Impact pick drive control system

2.2 Working Process of the Multi-impact Drum

Figure 4 shows the cutting process of the multi-impact drum. The drum moves linearly at the traction speed $v$, and at the same time drives the picks to rotate at the speed $n$. At this time, driven by the impact pick driver, the picks (No.1–6) in contact with coal will make a reciprocating impact motion along its axis with the impact force $F_c$. At this time, the other picks (No.7-12) are not involved in cutting as energy storage picks, so they do not impact. When the drum rotates until the No.6 pick leaves the coal and the No.12 pick starts to contact the coal, the working picks become No.1 to No.5 picks and No.12 pick, which are responsible for cutting and impact movement; The picks become the 6–11 picks and only do idling. Such a reciprocating cycle is the working process of the multi-impact cutting drum.
2.3 Coal-breaking Mechanics Model of Multi-impact Drum

2.3.1 Cutting Mechanics Model of Pick

Build the pick model at any position on the drum as shown in Figures 5 and 6, and make assumptions:

(1) The pick, seat, and drum are assumed to be rigidly connected and regarded as a whole.

(2) The pick is assumed to be concentrated and the point of action is at the tip of the pick.

As shown in Figure 5, a global coordinate system is constructed on the drum. The origin $O$ is located at the center of the drum end surface, and the $X$, $Y$, and $Z$ axes point to the traction direction, the vertical upward direction and the goaf direction respectively. Then a local coordinate system is established at the tip of the pick. The origin $O_1$ is at the tip of the pick, and the $X_1$, $Y_1$, and $Z_1$ axes are consistent with the $X$, $Y$, and $Z$ axes respectively. The $\theta_{x_i}$ represents the angle between any pick axis $O_1O_2$ and the $X_1$ axis. Similarly $\theta_{y_i}$ represents the angle between $O_1O_2$ and the $Y_1$ axis, and $\theta_{z_i}$ represents the angle between $O_1O_2$ and the $Z_1$ axis. As shown in Figure 6, in order to simplify the model, the pick is represented by $O_1O_2$. And the lateral force $Z_0$, feed resistance $X_0$, cutting resistance $Y_0$ and impact force $O_0$ on any pick are represented by $z_i$, $x_i$, $y_i$, $o_i$. Among them, $Z_0$, $X_0$, and $Y_0$ are perpendicular to each other, and $O_0$ is parallel to the pick axis $O_1O_2$.

In addition, assuming that the resultant force applied to the pick is along the $O_1O_2$ direction. This value is related to the angle defined in Figures 5 and 6. And is related to the position angle $\varphi_i$ of the pick tip radial line relative to the $Y$ axis, where $\varphi_i$ is shown in Figure 7.

Combined with Figures 5-7, it can be obtained that the feed resistance $x_i$, the cutting resistance $y_i$, the lateral force $z_i$ and the impact force $o_i$ experienced by the pick $i$ when the drum is at a non-specific position are in the global coordinate system:

$$
\begin{align*}
F_{x_i} &= -y_i \cos \varphi_i - x_i \sin \varphi_i - n_i o_i \cos \theta_{x_i} \\
F_{y_i} &= y_i \sin \varphi_i - x_i \cos \varphi_i - n_i o_i \cos \theta_{y_i} \\
F_{z_i} &= z_i + n_i o_i \cos \theta_{z_i}
\end{align*}
$$

where $F_{x_i}$, $F_{y_i}$, and $F_{z_i}$ are the force of the pick on the $X$, $Y$, $Z$ axis, $n_i$ is the number of impacts of the $i$-th pick, and is related to the impact frequency and working time of the pick.

2.3.2 Cutting Mechanics Model of Drum

The force of the multi-impact drum is related to the
force of all picks participating in the work. And it is the result of the collection of forces on all picks participating in the work. The force is shown in Eq. (2), and the coordinate system is the same as that shown in Figure 5.

\[
\begin{align*}
F_x &= \sum_{i=1}^{N} F_{x_i} = \sum_{i=1}^{N} \left( y_i \cos \phi_i - x_i \sin \phi_i - n_i \rho_i \cos \theta_i \right) \\
F_y &= \sum_{i=1}^{N} F_{y_i} = \sum_{i=1}^{N} \left( y_i \sin \phi_i - x_i \cos \phi_i - n_i \rho_i \cos \theta_i \right) \\
F_z &= \sum_{i=1}^{N} F_{z_i} = \sum_{i=1}^{N} \left( z_i + n_i \rho_i \cos \theta_i \right)
\end{align*}
\]

where \( N_{jg} \) is the total number of picks involved in cutting.

### 3 The Influence of Multiple Factors on the Performance of the Multi-impact Drum

#### 3.1 Simulation Plan

Considering that the study object is based on the working performance of the multi-impact drum on hard seam. The coal hardness, the impact frequency of picks, and the drum speed are selected as variables. The parameters of the scheme and coal attributes are shown in Table 1.

| Cutting depth /mm | Traction speed /m-min\(^{-1}\) | Coal hardness | Impact frequency /Hz | Drum speed /r-min\(^{-1}\) |
|-------------------|-------------------------------|---------------|----------------------|-----------------------------|
| 900               | 10                            | \( f_4 \)     | 4                    | 30                          |
|                   |                               | \( f_5 \)     | 6                    | 35                          |
|                   |                               | \( f_6 \)     | 8                    | 40                          |

The orthogonal experiment method shown in Figure 8 is used to match the above three variable parameters. The 27 nodes of the cube in the figure represent all 27 combinations of operating conditions, and the 9 nodes marked with emphasis represent the combination of orthogonality. In this case, let A be the coal hardness, B the impact frequency of picks, and C the drum speed. The simulation scheme is shown in Table 2.

#### Table 2 The scheme of orthogonal test

| Scheme No. | Coal hardness | Impact Frequency /Hz | Drum speed /r-min\(^{-1}\) |
|------------|---------------|----------------------|-----------------------------|
| 1          | \( f_4 \)     | 4                    | 30                          |
| 2          | \( f_4 \)     | 6                    | 35                          |
| 3          | \( f_4 \)     | 8                    | 40                          |
| 4          | \( f_5 \)     | 4                    | 40                          |
| 5          | \( f_5 \)     | 6                    | 30                          |
| 6          | \( f_5 \)     | 8                    | 35                          |
| 7          | \( f_6 \)     | 4                    | 35                          |
| 8          | \( f_6 \)     | 6                    | 40                          |
| 9          | \( f_6 \)     | 8                    | 30                          |

### 3.2 Cutting model of multi-impact drum

#### 3.2.1 Geometry model of drum

In order to be able to clearly simulate the impact effect of the picks of the multi-impact drum, the CATIA software was used to establish a model of drum. The internal hydraulic system structure was ignored when modeling, and a simplified model was established. According to the MG500/1180-WD shearer, the key structural parameters of the drum are determined as shown in Table 3. The pick arrangement of the shearer selects the sequential configuration method, the spiral cut line distance is set to 80mm, and the pick installation angle is set to 50°. After importing EDEM, as shown in Figure 9, use the ‘merge’ command to merge the parts other than the picks into a whole named ‘gun tong’, and then name the picks ‘1-1, 1-2, 4-18’ in the order of arrangement, etc..

| Drum width /mm | Bore diameter /mm | Drum diameter /mm | Helix angle /° |
|---------------|-------------------|-------------------|---------------|
| 900           | 650               | 1800              | 25            |
3.2.2 Coal model

In order to facilitate the study of the cutting effect of the multi-impact drum, the coal model assumed that a free surface with a similar shape to the outer envelope surface of the drum had been cut. According to the drum size, it is established as shown in Figure 10(a) as 1500mm×1000mm×2000mm. And a particle radius of 13.2mm is set to fill it with particles as shown in Figure 10(b).

In order to make the coal model have similar mechanical properties, the inter-particle contact model was changed to BPM. The bond settings include unit normal stiffness, unit tangential stiffness, bond ultimate normal strength, ultimate tangential strength, and bond radius. Among them, the stiffness of the coal was related to the constitutive parameters of the coal material, the normal stiffness $S_n$ was related to the elastic modulus $E$, and the tangential stiffness $S_t$ was related to the shear modulus $G$. The conversion method is:

$$\begin{align*}
S_n &= \frac{E}{l} \\
S_t &= \frac{G}{l}
\end{align*}$$

(3)

where $l$ is the particle spacing.

The ultimate normal strength represented the ultimate compressive strength $\sigma_n$ of the coal, which need to be obtained according to the empirical relationship between coal hardness and compressive strength:

$$\sigma_n = 10 \cdot f$$

(4)

Calculated from the above formula, the ultimate normal strength $\sigma_n$ of bond at the hardness values $f_4$, $f_5$, and $f_6$ were 40MPa, 50MPa, and 60MPa respectively. The shear strength $\tau$ and tensile strength $\sigma_l$ were based on the three-dimensional ultimate strength empirical relationship ($\sigma_y:\tau:\sigma_l=100:10~40:3~10$) to obtain. In order to further determine the coal hardness and bonding parameters, refered to the common seam geological conditions based on the existing hardness values, and approximately selected coal measures with reasonable values.

Table 4 shows some mechanical parameters of coal measures in a certain mining area [21]. According to the three-dimensional ultimate strength empirical relationship, the corresponding tensile strength value ranges of $f_4$, $f_5$, and $f_6$ were reduced, that was, the hardness value $f_4$ corresponds to 3~4 MPa, the hardness value $f_5$ corresponds to 4~5 MPa, the hardness value of $f_6$ corresponds to 5~6MPa. If there were multiple coal measures in the table that met the above range, selected the group with the largest elastic modulus.

| Scheme No. | Density (kg·m⁻³) | Elastic Modulus (GPa) | Shear Modulus (GPa) | Poisson's Ratio | Cohesion (MPa) | Friction Angle (°) | Tensile Strength (MPa) |
|------------|------------------|----------------------|---------------------|----------------|----------------|--------------------|-----------------------|
| 1          | 1420             | 4.2                  | 1.72                | 0.22           | 2.11           | 29.5               | 5.6                   |

Table 4 Mechanical parameters of coal measures
The coal measures corresponding to the hardness values \( f_4, f_5, \) and \( f_6 \) after screening were No.6, No.4, and No.1. After determining the coal parameters, in order to ensure the consistency of the structure, it was assumed that the hardness values \( f_4, f_5, \) and \( f_6 \) corresponded to the coal particle parameter density values. Finally, combined with formula (3) to determine the coal material parameters and bonding parameters at each hardness as shown in Table 5.

### Table 5  Material parameters and bonding parameters under different hardness

| Hardness | \( f_4 \)      | \( f_5 \)      | \( f_6 \)      |
|----------|----------------|----------------|----------------|
| Poisson’s ratio | 0.15 | 0.17 | 0.22 |
| Shear modulus /\( \text{Pa} \) | \( 9.56 \times 10^8 \) | \( 1.62 \times 10^8 \) | \( 1.72 \times 10^8 \) |
| Density / (\( \text{kg} \cdot \text{m}^{-3} \)) | 1420 | 1420 | 1420 |
| Coefficient of restitution | 0.45 | 0.45 | 0.45 |
| Coefficient of static friction | 0.48 | 0.48 | 0.48 |
| Coefficient of rolling friction | 0.18 | 0.18 | 0.18 |
| Normal stiffness per unit area/(\( \text{N} \cdot \text{m}^{-1} \)) | \( 8.33 \times 10^{10} \) | \( 1.439 \times 10^{11} \) | \( 1.591 \times 10^{11} \) |
| Shear stiffness per unit area/(\( \text{N} \cdot \text{m}^{-1} \)) | \( 3.62 \times 10^{10} \) | \( 6.136 \times 10^{10} \) | \( 6.515 \times 10^{10} \) |
| Critical normal stress /\( \text{Pa} \) | \( 4 \times 10^7 \) | \( 5 \times 10^7 \) | \( 6 \times 10^7 \) |
| Critical shear stress /\( \text{Pa} \) | \( 1.6 \times 10^7 \) | \( 2 \times 10^7 \) | \( 2.4 \times 10^7 \) |
| Bonded disk radius /m | 0.012 | 0.012 | 0.012 |

#### 3.2.3 Drum movement parameters

Set the material of the multi-impact drum model to steel, and its parameters are shown in Table 6, then added linear motion, the motion direction was along the X axis, and the motion speed was set to 0.167m/s based on the traction speed of 10m/min. Added rotation movement, set the start and end time of rotation, the rotation axis was set at the center of mass of the drum to coincide with the center axis of the drum, the speed was set to the corresponding value according to the parameter needs, and the rotation axis moves with the geometry option was checked.

In addition, the reciprocating impact motion of the picks need to be considered, so an additional linear motion should be added, and the working picks in the cutting state was set as the impact part. According to the impact frequency of 4Hz, 6Hz, 8Hz, set the pick perform an impact movement every 0.25s, 0.167s, and 0.125s. Suppose the impact pressure was \( 1 \times 10^4 \text{N} \). Since there was no setting related to impact pressure in EDEM, it need to be converted into motion parameters with the same effect for simulation. The conversion of specific impact parameters can be determined by Eq. (5).

\[
\begin{align*}
\alpha &= \frac{F}{m} \\
\tau &= \frac{2l}{\alpha}
\end{align*}
\]

where \( m \) is the pick quality, \( F \) is the pick impact pressure, \( \alpha \) is the acceleration, \( l \) is the maximum impact stroke of pick, \( \tau \) is the acceleration time.

Since the pick used in this simulation is about 1.65kg and the maximum impact stroke was 0.01 m, it can be determined that the acceleration was \( 6060.6 \text{m} \cdot \text{s}^{-2} \) and the acceleration time was 0.002s. Due to the short impact and reset time, in order to ensure the accurate reset of the pick, the impact process of the pick was simplified and the simulation parameters were set by the combination of man and machine for calculation. Took the pick ‘1-1’ with a traction speed of 10m/min, coal hardness of \( f_6 \), impact frequency of 4Hz, and drum speed of 35r/min at a certain moment as an example. The specific settings of impact motion parameters are shown in Figure 11.
After the pick reached the maximum stroke, an impact movement in the opposite direction was set on it to realize the pick reset. By adopting this method to similarly set other picks, the reciprocating movement of all impact picks on their axes and the overall rotary cutting movement of the drum can be realized. Set the simulation calculation time step to 15\% and the grid size to 2R_{min}. Taking into account that the drum speed was 30r/min, it took at least 2s to make one revolution. To ensure the validity of the simulation results, the total simulation time was 2s, and finally the coal breaking model and cutting process of the multi-impact drum are obtained as shown in Figure 12 and 13 shown.

3.3 Analysis of the influence of multiple factors on the working performance of drum

In order to reflect the working performance of the multi-impact drum under different conditions, this paper used the coal breaking rate and specific energy consumption as the evaluation indexes. The coal breaking rate index was calculated by the EDEM post-processing module under each simulation scheme. The number of remaining bonds in the coal was obtained, and the number of cut bonds in the simulation time of the multi-impact drum was obtained, and the ratio of this value to the total amount of bonds in the coal model was the coal breaking rate of the drum. The post-processing module counted the average value of the drum torque under each simulation scheme, and calculated the specific energy consumption of the drum according to Eq. (6), and finally obtains the simulation results under each scheme as shown in Table 6.
\[ H_w = \frac{mTN}{9550 \times 3600V_c} \]  

where \( H_w \) is the Specific energy consumption, \( t \) is the cutting time, \( V_c \) is the volume of cut coal, \( n \) is the drum speed, \( T_M \) is the drum torque average.

### Table 6  Simulation results of multi-impact drum

| Scheme No. | Coal hardness | Impact frequency /Hz | Drum speed /r-min\(^{-1}\) | Number of cut bonds | Average drum torque /(N-m) | Falling coal volume /m\(^3\) | Specific energy consumption /(kWh-m\(^3\)) |
|------------|---------------|-----------------------|-----------------------------|-----------------------|---------------------------|-------------------------------------|------------------------------------------|
| 1          | f4            | 4                     | 30                          | 20222                 | 1.2948×10\(^7\)           | 0.1464                             | 1.5438                                   |
| 2          | f4            | 6                     | 35                          | 23239                 | 8.8142×10\(^6\)           | 0.1682                             | 1.0699                                   |
| 3          | f4            | 8                     | 40                          | 25915                 | 6.3455×10\(^6\)           | 0.1876                             | 0.7872                                   |
| 4          | f5            | 4                     | 40                          | 29131                 | 6.2766×10\(^6\)           | 0.2109                             | 0.7423                                   |
| 5          | f5            | 6                     | 30                          | 21073                 | 1.2271×10\(^6\)           | 0.1525                             | 1.4040                                   |
| 6          | f5            | 8                     | 35                          | 24646                 | 7.9992×10\(^6\)           | 0.1784                             | 0.9130                                   |
| 7          | f6            | 4                     | 35                          | 24944                 | 1.0812×10\(^6\)           | 0.1805                             | 1.2193                                   |
| 8          | f6            | 6                     | 40                          | 27414                 | 9.2484×10\(^6\)           | 0.1984                             | 1.0845                                   |
| 9          | f6            | 8                     | 30                          | 20050                 | 1.5482×10\(^6\)           | 0.1451                             | 1.8168                                   |

Using the range method to analyze the data in Table 6, the purpose was to find the optimal combination of these factors at each level. Table 7 shows the extreme difference statistics of each level factor condition in nine groups under the corresponding evaluation indexes, where K11 represents the average coal breaking rate of the three factors at the first level, and similarly, K12 and K13 represent three factors at the second level and the third level of the average coal breaking rate. R1 is the extreme difference value under the condition of the coal breaking rate evaluation index, which represents the deviation of the impact of different levels on the breaking result under a single factor. The greater the extreme difference, the greater the impact on the coal breaking rate. It can be seen from Table 7 that the hardness of coal is the most important factor among the three, and the rotation speed of the drum takes the second place. The greater the coal breaking rate, the better the work performance, so under the index of coal breaking rate, the optimal scheme combination was A2B1C3. K21, K22, and K23 respectively represent the average value of cut specific energy consumption of the three factors at each level, and R2 is the range of the index, indicating the deviation of the impact of different levels of a single factor on the cut specific energy consumption. The greater the range, the greater the impact on cutting specific energy consumption. It can be seen from Table 7 that the rotation speed of the drum is the most important factor among the three, and the hardness of coal is the second. Since the lower the specific energy consumption of cutting, the better the work performance. Therefore, under the index of specific energy consumption of cutting, the optimal scheme combination is A2B1C3.

### Table 7  Differential data analysis

| Influencing factors | Coal hardness | Impact frequency /Hz | Drum speed /r-min\(^{-1}\) |
|---------------------|---------------|-----------------------|-----------------------------|
| K_{11}              | 0.3121        | 0.3240                | 0.3146                      |
| K_{12}              | 0.3251        | 0.3172                | 0.3160                      |
| K_{13}              | 0.3184        | 0.3144                | 0.3250                      |
| R_1                 | 0.0129        | 0.0096                | 0.0104                      |
| Optimal Scheme      | A_2           | B_1                   | C_3                         |
| K_{21}              | 1.1326        | 1.1685                | 1.6032                      |
| K_{22}              | 1.0198        | 1.1851                | 1.0664                      |
| K_{23}              | 1.3886        | 1.1873                | 0.8713                      |
| R_2                 | 0.3688        | 0.0188                | 0.7318                      |
| Optimal Scheme      | A_2           | B_1                   | C_3                         |

Though the optimal scheme combinations corresponding to the two evaluation indexes in Table 7 are the same, the influence of each factor on the work performance is not same. In order to obtain the final ranking of the influence factors, a matrix analysis method was specially introduced. Assuming that the orthogonal test is l factor m level, the index mean value of factor A_i at the jth level was k_{ij}, if the index was bigger for the whole system, the better, then let K_i=\frac{k_{ij}}{k_{ij}}, and established the matrix shown in Eq. (7); Otherwise, set K_i=1/k_{ij} to establish the matrix shown in Eq. (8).
Assumed energy consumption, the better the drum performance. When the cutting rate, the better the drum performance. Then according to Eq. (11), the weight matrices \( \omega_1 \) and \( \omega_2 \) under two indexes can be obtained respectively:

\[
\omega_1 = M_1 T_1 S_1 = \begin{bmatrix}
0.3121 & 0 & 0 \\
0.3251 & 0 & 0 \\
0.3184 & 0 & 0 \\
0 & 0.3240 & 0 \\
0 & 0.3172 & 0 \\
0 & 0.3144 & 0 \\
0 & 0 & 0.3146 \\
0 & 0 & 0.3160 \\
0 & 0 & 0.3250
\end{bmatrix}
\]

\[
\omega_2 = M_2 T_2 S_2 = \begin{bmatrix}
0.0096 & 0 & 0 \\
0.0104 & 0 & 0 \\
0.0129 & 0 & 0 \\
0.0329 & 0 & 0 \\
0.0329 & 0 & 0 \\
0.0329 & 0 & 0 \\
0.0329 & 0 & 0 \\
0.0329 & 0 & 0 \\
0.0329 & 0 & 0
\end{bmatrix}
\]

Finally, the evaluation index weight matrix was established by Eqs. (7)-(10):

\[
\omega = \begin{bmatrix}
M_T S_1 \\
M_T S_2 \\
\vdots \\
M_T S_m
\end{bmatrix} = \begin{bmatrix}
\omega_1 \\
\omega_2 \\
\vdots \\
\omega_m
\end{bmatrix}
\]
In order to obtain the optimal scheme based on the two evaluation indexes, the two weight matrices need to be averaged to obtain the total weight matrix $\omega$:

$$\omega = \frac{\omega_1 + \omega_2}{2} = \frac{A_1 + A_2}{2} = A_3$$

$$= \begin{bmatrix}
0.1053 \\
0.1125 \\
0.0990 \\
0.0514 \\
0.0503 \\
0.0499 \\
0.1096 \\
0.1388 \\
0.1597 \\
\end{bmatrix}$$

Table 8  Performance comparison between multi-impact drum and traditional drum

| Scheme No. | Coal hardness | Impact frequency /Hz | Drum speed /(r·min\(^{-1}\)) | Number of cut bonds | Average drum torque /(N·m) | Falling coal volume /m\(^3\) | Specific energy consumption /(kWh·m\(^{-3}\)) |
|------------|--------------|----------------------|-----------------------------|---------------------|---------------------------|-----------------------------|-----------------------------------------------|
| 1          | f5           | 4                    | 40                          | 29131               | 6.7266\times10^4         | 0.2109                      | 0.7423                                         |
| 2          | f5           | /                    | 40                          | 23330               | 6.8766\times10^4         | 0.1689                      | 0.9476                                         |
As can be seen from the above table, in term of coal breaking rate, the amount of coal dropped by the non-impact drum was 23,330. Compared with the non-impact drum, the amount of coal dropped by the multi-impact drum was increased by about 24.86%. The specific energy consumption of the non-impact drum for cutting is 0.9476kWh·m⁻³. Compared with the non-impact drum, the multi-impact drum reduced coal drop by about 26.41%. It can be seen that the multi-impact drum was more suitable for hard seam than traditional drum.

4 Field Test Analysis of Working Performance for Multi-impact Drum

4.1 Design of multi-point impact cutting test-bed

In order to explore the actual working performance of the multi-impact coal breaking technology, a multi-impact cutting test-bed is designed as shown in Figure 14. The drum is simplified, that is, it was designed as a cutting disc and set up 6 picks.

As shown in the figure above, the whole machine test-bed consists of cutting mechanism, ranging arm, three plunger hydraulic drive linear motor, double piston hydraulic drive rotary motor, hydraulic oil tank, water-cooled cooler, hydraulic control unit, and oil conveying pipe. The cutting mechanism is shown in Figure 15, consisting of a hydraulic motor, a high-pressure rotary joint, a cutting disc and 6 hydraulic impact picks. The hydraulic oil successively enters the impact cylinder cavity through the high-pressure rotary joint, cutting disc pipe, and pick seat, then drives the pick for impact movement by driving the piston. In addition, the three-plunger hydraulic drive linear motor is used to control multiple hydraulic cylinders to follow the plunger to reciprocate. And by controlling the reciprocating frequency of the plunger to control the movement frequency of the hydraulic cylinders, so as to achieve the impact motion of picks with controllable frequency. The double-piston hydraulic drive rotating motor is used to control the height of ranging arm and the rotation of cutting disc.

4.2 Cutting performance test of multi-impact technology

Taking into account the limited testing conditions, the seam hardness of the working face was f3. The pick impact and non-impact were combined to test, and the cutting disc speed was set to 40r·min⁻¹. After starting the test device, first let the disc cut for 3 minutes without picks impact, and then cut for 3 minutes with impact. Considering that the test conditions were difficult to accurately count the broken coal volume under the two cutting methods, and the coal breaking rate and specific energy consumption in the simulation experiment cannot be used as indicators to evaluate the coal breaking performance. Therefore, the cutting power in the statistical test process is shown in Figure 16, and the cutting resistance was obtained according to Eq. (12). This value was used as an index to analyze the coal breaking performance of the cutting disc in different working modes.
\[ F = \frac{P}{2m} \]  \quad (12)
According to the above formula, the cutting resistance at each time point is shown in Table 9. It was calculated that the average cutting resistance under impact and non-impact state of the picks were 4473N and 5390N. It can be seen that multi-impact cutting can reduce the cutting resistance. The cutting resistance was over 17.22%, which was basically in line with the trend stated in the aforementioned multi-impact and non-impact comparative simulation experiment results.

| Time   | Impact | Cutting resistance /N | Time   | Impact | Cutting resistance /N |
|--------|--------|-----------------------|--------|--------|-----------------------|
| 14:14:00 | No    | 4820                  | 14:17:00 | Yes    | 3871                  |
| 14:14:20 | No    | 7296                  | 14:17:20 | Yes    | 4944                  |
| 14:14:40 | No    | 5188                  | 14:17:40 | Yes    | 5002                  |
| 14:15:00 | No    | 5107                  | 14:18:00 | Yes    | 4286                  |
| 14:15:20 | No    | 5125                  | 14:18:20 | Yes    | 4098                  |
| 14:15:40 | No    | 5356                  | 14:18:40 | Yes    | 4409                  |
| 14:16:00 | No    | 5023                  | 14:19:00 | Yes    | 4875                  |
| 14:16:20 | No    | 5506                  | 14:19:20 | Yes    | 4378                  |
| 14:16:40 | No    | 5174                  | 14:19:40 | Yes    | 4226                  |
| 14:16:59 | No    | 5269                  | 14:19:59 | Yes    | 4641                  |

5 Conclusions

(1) Designed a multi-impact drum structure, explained the working process of the multi-impact drum, and established a mechanical model for the cutting method.

(2) The discrete element simulation method was used to analyze the influence of multiple factors on the performance of the multi-impact drum. The coal breaking rate and the cutting specific energy consumption were used as indexes, and the best cutting scheme was obtained by matrix analysis. The best cutting scheme was that the coal hardness was $f_5$, the impact frequency was 4Hz, and the drum speed was $40\text{r}\cdot\text{min}^{-1}$.

(3) Under the same working condition, the working performance of the multi-impact drum and the traditional drum was compared. In term of coal breaking rate, the amount of coal dropped by the non-impact drum was 23,330, and the amount of coal dropped by the multi-impact drum was increased by about 24.86%. In term of specific energy consumption, the non-impact drum cutting was $0.9476\text{kWh}\cdot\text{m}^{-3}$, and the multi-impact drum was about 26.41% lower than that of the non-impact drum.

(4) A simplified test-bed for multi-impact cutting was designed, and industrial test was carried out. The cutting resistance was used as an index to analyze the coal breaking performance of the pick under impact and non-impacted. After calculation, the multi-impact type can reduce cutting resistance by more than 17.22%, which is basically in line with the trend stated in the simulation experiment.

6 Declaration

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Availability of data and materials
The datasets supporting the conclusions of this article are included within the article.

Authors’ contributions
The author’s contributions are as follows: Qiang Zhang was in charge of the whole trial; Cong Wang wrote the manuscript; Ying Tian and Xu Zhang assisted with sampling and laboratory analyses.

Competing interests
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References
[1] G S Wu, W J Yu, J P Zuo, et al. Experimental investigation on rockburst behavior of the rock-coal-bolt specimen under different stress conditions[J]. entific Reports, 2020, 10(1):7556.
[2] K Wodarski, J Bijańska, A Gumiński. The method of validity evaluation of hard coal excavation in residual seam parts[J]. Archives of Mining ences, 2017, 62(4):675-687.
[3] X Liu, L Zhao, W Zhou, et al. Influence law of kinematic parameters on the stress of drum cutting coal gangue[J]. Muan XuebaoJournal of the China Coal Society, 2018, 43(10):2926-2933.
[4] W L Yin, Y S Pan, Z H Li, et al. On the effect of deep coal seam gas to coal mechanical properties[J]. Journal of Experimental Mechanics,2016,31(06):858-865.
[5] B A Paola, C T Barreto. A microscopic study on kerfs in rocks subjected to abrasive waterjet cutting[J]. Wear, 2020, s448-449:203210.
[6] J L Cheng, Z H Jiang, W F Han, et al. Breakage mechanism of hard-rock penetration by TBM disc cutter after high pressure water jet precutting[J]. Engineering Fracture Mechanics, 2020.
[7] L Engelmeier, M Kretzschmar, S Pollak, et al. Schneiden und Bohren mit flüssigem Kohlendioxid[J]. Chemie Ingenieur Technik, 2016, 88(5):672-676.
[8] C Shet, X Deng, A E Bayoumi. Finite element simulation of high-pressure water-jet assisted metal cutting[J]. International Journal of Mechanical ences, 2003, 45(s 6-7):1201-1228.
[9] Y B COHENA, C MAVROIDIS, M BOUZIT, et al. Virtual reality robotic telesurgery simulations using MEMICA haptic system. Proceedings of SPIE’s 8th Annual International Symposium on Smart Structures and Materials, Newport, USA, March 5–8, 2001: 1–8.
[10] Y Kang, X C Wang, Y Y Lu, et al. Experimental study of rock breaking by a three wing, abrasive jet assisted drill bit[J]. Journal of China University of Mining & Technology, 2012, 41(02):212-218.
[11] X Q Duan, H X Jiang, C W Guo. Numerical studying of cutting pick rotary broken rock with centralized high pressure water jet[J]. Coal Mining Technology, 2016, 21(04):10-14.
[12] C S Liu, Y Y Xu, D G Li, et al. Mechanical mechanism and model of rock breaking by edge tooth disk[J]. Journal of China Coal Society, 2018, 43(01):272-279.
[13] C S Liu, H Yuan, D G Li. Study on broken coal-rock load simulation and pulverization of axial vibration of disc cutter[J]. Coal Science and Technology,2020,48(01):189-195.
[14] C S Liu, Y T Liu, Y Y Xu, et al. Study on load characteristics of cutting coal and rock with cutter tooth on disk cutter[J]. Coal Science and Technology,2019,47(07):176-182.
[15] T Liu, Z X Wang, Z A Cui, et al. Research on the process influence of laser pre-drilling on granite surface[J]. Applied Laser, 2017,37(04):580-585.
[16] H Xie, Y Zhou, H R Dong, et al. Experimental study on laser assisted rock breaking[J]. Journal of Oil and Gas Technology,2013,35(04):152-154+157+170.
[17] M Y Li, B Han, S Y Zhang, et al. Study on laser assisted rock breaking law and mechanical properties[J]. Applied Laser, 2015,35(03):363-368.
[18] S B Li, K X Li, L G Zhang. Influence of laser power and irradiation time for laser rock fragmentation[J]. China Energy and Environmental Protection,2017(03):121-123+127.
[19] Q Zhang, J M Liu, J Y Gu, et al. Research on breaking characteristics of the rock under different unloading conditions[J]. Chinese Journal of Applied Mechanics,2019, 36(03):727-733+767.
[20] Q Zhang, G Q Sun, J W Suo, et al. The 3D numerical simulation of deep granite borehole unloading[J]. Chinese Journal of Applied Mechanics,2017,34(05):988-994+1021.
[21] Q Zhang, C Wang, Y Tian. Research on coal breaking characteristics of presplitting assisted impact pick[J]. Journal of China Coal Society, 2019, 44(10):3209-3222.

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