Study on drilling mechanism of combined bit in hard coal seam

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Abstract. Borehole pressure relief can effectively reduce the accumulation of elastic energy of working face and surrounding rock mass, and reduce the regional impact risk. But in hard coal seam, drilling jam, holding and other dynamic phenomena often occur in drilling, which seriously reduces drilling efficiency. Therefore, aiming at the problem of poor coal breaking effect of traditional geological drills in hard coal and rock, the coal breaking characteristics of new type combined drills are studied by theoretical analysis and numerical simulation. Considering the traction, rotation and impact movement in practical work, the trajectory model of combined drills is put forward. The coal breaking characteristics of the two kinds of drills are compared and analysed from the aspects of the difficulty of coal breaking and the force fluctuation of the drill bit. The results show that the combined bit can reduce the difficulty of coal breaking by 50% when its hardness value is twin 6, and the combined bit can reduce the force of nearly 7000N in hard coal and rock in the fluctuation of force acting on the geological bit. Therefore, the study of coal breaking characteristics of the combined bit can effectively improve the special rock mass such as broken hard coal and rock.

1. Introduction
With the increasing depth of coal mining in our country, more and more mines appear rock burst phenomenon, as described in document [1, 2]: rock burst is one of the coal and rock dynamic phenomena in coal mining, which can lead to sudden destruction of coal and rock, roof fall, bracket breakage and even ground vibration and other safety accidents. Drilling pressure relief technology can reduce the regional impact risk by reducing the accumulation of elastic energy of working face and surrounding rock mass, but there are significant differences in drilling efficiency in different hardness coal seams, especially in hard coal seams where drilling often occurs such dynamic phenomena as sticking and holding drills. For this reason, high-efficiency combined drill bit adds lateral cutter in the process of drilling coal and rock with small aperture in view of complex coal and rock conditions. The step-by-step reaming impact motion of the drilling tool can realize synchronous pre-cracking inside the coal body and reduce the breaking impedance and viscosity of hard coal, thus improving the efficiency of drilling work. Therefore, it is of great significance to study the coal breaking characteristics of the new combined drill bit.

At present, most of the research on the evaluation of coal and rock breaking performance at home and abroad focuses on the angle of traditional geological drills. Based on ABAQUS software, Li [3]
obtained the variation law of rock breaking efficiency under different initial in-situ stress conditions; Li [4] based on fractal theory, gave the actual physical meaning of the fractal dimension of the evaluation of rock breaking resistance curve and other characteristics. On the other hand, Liu [5] comprehensively evaluated the actual performances of different diameter bits from the aspects of specific energy consumption, loss rate of geological bits and stress of geological bits; Yang [6] analyzed the rock-breaking performances of geological bits using cutting maps; Yang [7] and other factors affecting rock-breaking resistance based on coal fragmentation.

Because of the different coal breaking mechanism, the traditional geological bit or gas-liquid jet cannot be used to analyze the coal breaking mechanism of the combined bits specially used for drilling coal and rock. At present, there is a relatively lack of coal breaking performance evaluation system under complex coal seam conditions. It is necessary to conduct a comprehensive analysis of new coal breaking technology and new coal seam geological conditions. In this paper, the combined bit is taken as the research object, and the rotary, drilling and reaming motion of the bit are considered by theoretical analysis and numerical simulation. The coal breaking trajectory is determined. Based on this, the coal breaking model of the geological bit is established, and the coal breaking characteristics of the traditional geological bit and the combined bit are compared and analyzed.

2. Analysis of reaming trajectory of combined bit

Before analyzing the coal breaking characteristics of combined drills, the action form of coal breaking should be determined, that is, the movement track of the drill, and the coal breaking trajectory model of the drill should be established by combining rotary motion and drilling motion, and the analytical solution of the coal breaking action range can be obtained [8].

Figure 1 is the coal breaking trajectory curve of drill bit. R is the radius of reaming hole, R is the diameter of drilling hole. In order to establish the trajectory model of coal breaking, it is assumed that only the rotary motion will move to point a after t seconds. Because the rotary motion is synchronized with the drilling motion, the distance from point a to point B is the drilling distance after t seconds. In the local enlarged map of coal breaking trajectory, the arc protrusion on the curve of coal breaking trajectory with B as the end point is the minor damage caused by reciprocating impact, and finally is the coal breaking area S of the drill bit.

\[
\begin{align*}
A &= R \sin(\theta + \beta - \alpha) \\
B &= R \cos(\theta + \beta - \alpha)
\end{align*}
\]

Let the analytic expression of circle O be:

\[x^2 + y^2 = R^2\]
In Figure 1, the travel distance can be set to $C$ by velocity $V$ and drilling time $t$, then the expression of $C$ and the equation of circle $O'$ are as follows:

$$C = \frac{\pi V}{60} t^2 + \frac{R}{2}$$

$$x^2 + y^2 = 1$$

(3)

In the formula, $C$ is travel distance, mm; $V$ is traction speed, m/min; $t$ is drilling time, s. Since the value of the ordinates of $C$ and $D$ points is $B$, the coordinates of $D$ points can be obtained from the $O'$ equation of the circle, so the area $S$ of the region can be calculated by definite integral.

$$S = \frac{\lambda}{2} \left[ 2d_1 + \frac{d_1(d - d_1)}{l} + 2vt_1 \sin \theta \right] (l_1 + vt_1 \cos \theta)$$

(4)

From the theoretical analysis of coal breaking area of drill bit, it can be seen that the main influencing factors of coal breaking area of combined drill bit are not only tool geometric parameters and drilling and rotary speed, but also the difference of initial drilling diameter and reaming diameter, which can significantly affect coal breaking area and efficiency. According to the theoretical area and actual drilling thickness, the theoretical coal breaking volume of drill bit can be obtained. At the same time, it is the simulation model for the following text. The basis is provided for the selection of volume parameters of coal to be broken.

3. Discrete element model for coal breaking with combined bit

The analysis of coal breaking trajectory of geological drill is based on three motion modes: rotation, traction and impact. At the same time, the analysis of three-dimensional geometric model in discrete element simulation is more idealized, which will not cause disturbance and further affect the simulation results [9-12] therefore, a single-tool drill is established by using Solidworks software. The simplified model is shown in Figure 2.

4. Comparison and analysis of coal breaking characteristics under different coal hardness

Because of the difficulty of complex coal seam mining and the limitation of research at home and abroad, this paper proposes more evaluation methods of coal breaking characteristics to enhance the credibility of research [13-16]. Particle aggregates can represent the shape of coal wall. The difficulty of coal breaking is determined by the total number of remaining bonds, that is, the less the total number of remaining bonds, the easier it is to break coal.

4.1. Comparison of Difficulties in Breaking Coal

Fracture development in coal breaking process is also related to the fracture of bond, which can reflect a certain degree of damage in coal body, and then reduce the difficulty of coal breaking by single geological bit. Therefore, if the degree of difficulty in breaking coal is epsilon and the number of broken bonds is $x$, the degree of difficulty in breaking coal is defined as:

$$\varepsilon = \frac{x}{b_1} \times 100\%$$

(5)
If the value of $E$ is greater than 100%, it shows that geological drill can cause fracture damage to coal body. The bigger the value, the better the development of cracks in coal body and the easier the coal breaking. If the value of $E$ is less than 100%, it shows that it is difficult for geological drill to break coal under this condition, which easily leads to the wear of geological drill bit and reduces the actual proportion of coal breaking particles. According to the above formula, the difficulty of coal breaking under different working conditions is obtained as shown in Table 1.

| Different Coal Rocks          | Difficulty Level $f_1$ Hardness Coal Rock | Difficulty Level $f_2$ Hardness Coal Rock | Difficulty Level $f_3$ Hardness Coal Rock |
|-------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|
| Combined Bit                  | 109.6%                                    | 113.7%                                    | 117.2%                                    |
| Traditional Geological Bit    | 101.3%                                    | 89.0%                                     | 59.1%                                     |

As can be seen from Table 1 above, combined drill bit can greatly reduce the difficulty of hard coal seam mining, and with the increase of coal hardness, the better the pre-cracking effect caused by the impact of geological drill bit. Traditional geological drills perform well in breaking twin-4 hardness coal, but the hardness increases dramatically. When the hardness value is twin-6, the degree of coal breaking difficulty under the two coal breaking methods is even 50%, which is close to two times. By importing the data of hardness value and coal breaking difficulty into MATLAB, the change fitting curve can be obtained as shown in Figure 3.

![Figure 3. Fitting curve of difficulty of breaking coal with hardness of coal and rock](image-url)

From the figure above, it can be seen that the traditional geological drill can effectively reduce the difficulty of coal breaking when the hardness value is below twin 3.5, but the difficulty of coal breaking increases rapidly after exceeding the hardness value. When the hardness value exceeds twin 4, the degree of difficulty decreases greatly, while the difficulty of coal breaking of combined drill is relatively stable, even when the hardness value reaches twin, it can effectively reduce the difficulty of coal breaking.

From the point of view of the difficulty of coal breaking, the combined bit can effectively reduce the difficulty of coal breaking for hard coal, and the pre-cracking performance is stable. It is suitable for all kinds of hard coal mining environment. However, when the hardness of coal is low, the pre-cracking performance of traditional geological bit is also acceptable.
4.2. Force Contrast of Bits

Figure 4 shows the variation tendency of drill bit stress with time for different hardness coal rock. It can be seen that the peak force of combined bit is lower than that of traditional bit under the same hardness, but there is no other obvious rule.

Combining the actual proportion of coal breaking particles, the difficulty of coal breaking and the stress analysis of geological drills, the combined drills, with the help of their impact pre-cracking effect, can obtain a higher actual proportion of coal breaking particles, effectively reduce the difficulty of coal breaking, and reduce the resistance of geological drills, prevent the wear of geological drills. At the same time, the higher the hardness of coal measures, the better the coal breaking performance of traditional geological drills.

5. Conclusion

The coal breaking characteristics of two kinds of geological drills under different coal body hardness are compared and analyzed from the point of view of coal breaking difficulty and geological drill force. In the degree of coal breaking difficulty, combined drill can greatly reduce the difficulty of hard coal seam mining. The harder the coal body is, the better the pre-cracking effect is. When the hardness value
is twin, the coal breaking difficulty of the two kinds of coal breaking technology is 50% different. In terms of force, the combined bit can reduce the crushing resistance, and the maximum force difference between the two geological bits is close to 7000N.

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