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INFLUENCE OF PICK LAYOUTS ON THE PERFORMANCE OF BOLTER MINER CUTTING HEAD

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Abstract: A bolter miner is a new type of mining machinery with cutting and anchoring functions. In order to study the best pick layout of bolter miner cutting head. Based on the constitutive relation of Holmquist-Johnson-Cook (HJC), three simulation models of different cutting heads were established, and the whole crushing process of coal-rock was simulated by finite element method (FEM). The influence of the cutting head on the cutting performance under the condition of different rotational speeds and pick layouts was intensively studied. The results show that the relationship of load fluctuation coefficient among the three pick layouts is as follows: sequential type > hybrid type I > checkerboard type. The circumferential pick layouts can reduce the load fluctuation coefficient of cutting head. The rotational speed from 20 to 40 r/min, the torque linearly decreases with the increase of rotational speed. The rotational speed increases from 40 to 50 r/min, the cutting torque is relatively stable. The specific energy of chessboard type is relatively higher than the other three cutting heads. The difference of specific energy between sequential type and hybrid type I is not more than 5.5%, and the reality of the simulation is verified by cutting experiments. The results were successfully applied to the first shield type bolter miner in China.

Keywords: *optimum: pick layout, bolter miner, FEM, coal-rock cutting, load fluctuation*

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1. INTRODUCTION

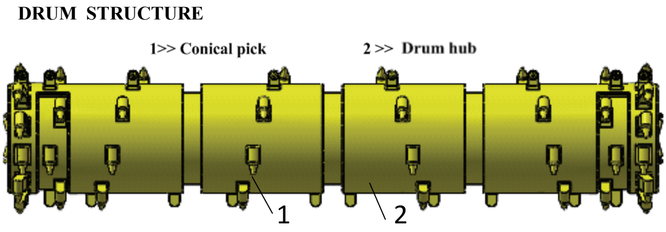
Coal-rock cutting is the core technology of coal mining. A bolter miner cutting head is one of the main equipments of the coal-rock cutting system (Gao et al. 2012; Ma 2017; Leeming et al. 2011; Vierhaus 2002). And the quality of its design directly affects the reliability, economy, and rapidity of the work being conducted. Owing to the short development time of a bolter miner, there have been few reports on its pick layout of a cutting head thus far, however, many scholars have conducted in-depth studies on other helical drums used in cutting equipment that we can learn some experience. For example, Zhang (2016) performed rock cutting tests, and investigated the effect of helical drums on different coals and rocks. Li (2011) proposed that cutting space and cutting depth reportedly influence the cutting force and specific energy. The drum load system was developed by FEM, and successfully applied to shearer. Zhao (2011) selected the best pick layout scheme of a shearer under different working conditions, and the cutting torque, cutting force and load fluctuation coefficient have been applied as indexes. Gunes (2007) studied the relationship between the blade wrap angle on a helical drum and the crushing effect, a forecasting formula for the cutting force was presented.

In conclusion, as an object of research, there is an essential difference between a bolter miner and a traditional helical drum. At present, there are no studies on the pick layout of a bolter miner cutting head, and thus improving the technology in this field is an urgent matter. Hence, this paper presents a simulation model of coal-rock fragmentation for a cutting head interacting with coal-rock, and the model is established by FEM (Heydarshahy 2017; Qiao et al. 2017a; Yu et al. 2014; Xu et al. 2015). The specific energy and load fluctuation are analyzed at various movement parameters, and the results will provide a quantitative basis for a performance evaluation of a cutting head.

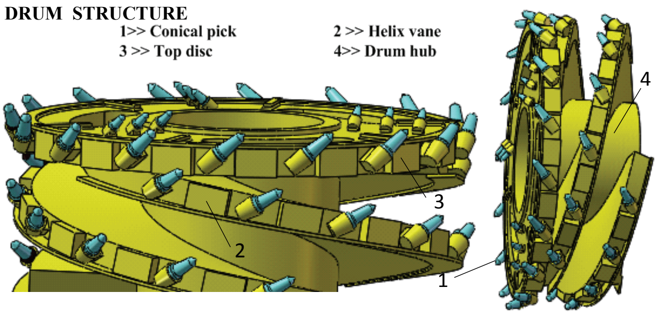
2. MECHANICAL MODEL OF CUTTING HEAD

2.1. BOLTER MINER

A bolter miner is a complete set of equipment that synchronizes the excavation and bolting-mesh support (Esterhuizen 2016; Rostami et al. 2015). The coal-rock is cut by the front-swinging cutting head of the miner, while bolt support is provided by the bolting machine installed at the rear of the bolter miner. Synchronous excavation and support construction was first realized by Australia's Tahmoo Coal Mine in May of 1991, marking the birth of the world's first bolter miner (Bertignoll 1995). Since then, bolter miners have been applied in the United States, South Africa, Australia and other countries, and have achieved good results (Vierhaus 2002). Until the beginning of the twenty-first century, bolter miners were used for coal-lane tunneling in China, but the progress was not impressive. A bolter miner cutting head is composed of the drum, pick-sites and conical picks. Unlike traditional shearers, the cutting head omits the helical vane, so the pick-sites are directly welded to the cutting head (Hoseinie et al. 2012), and the falling coal is transported to the belt conveyor through the front scraper impeller. In the traditional shearer, the pick-sites are welded on the helical vane, and the falling coal is thrown into the scraper conveyor and ejected by the spiral blade. The coal-rock fragments are somewhat larger in the bolter miner than in the shearer, and the different structures of the bolter miner cutting head and shearer helical drum lead to large differences in the mechanical properties of the two devices (Yasar 2017; Abdolreza 2013). The bolter miner cutting head moves by feed motion and rotation along the centerline of the roller, and the coal-rock is crushed by the rotation of different numbers of conical picks.



(a) Bolter miner



(b) Traditional shearer

Fig. 1. Structures of cutting heads in different mining equipment

2.2. MECHANICAL MODEL

Bolter miner cutting head is composed of a drum, pick-sites and conical picks. And the movement of cutting head is the synthesis of the drum rotation and the traction motion of bolter miner, the crushing process of coal-rock is accomplished by the drum rotation. And the force of coal-rock cutting can be divided into cutting force X_i, traction force Y_i and axial force Z_i, see Fig. 2.

(1) Cutting Force Analysis of the Conical Pick

According to the relevant literature [6, 10] about the cutting force of rock cutting, the cutting force X_i can be expressed as as follows:

$$X_i = 10\bar{A}ht\frac{0.35b+0.3}{b+Bh^{0.5}}k_1k_2k_3k_4\frac{1}{\cos\beta}+100f'k_{yj}\sigma_c S_d\,, \tag{1}$$

where S_d is abrasive area, σ_c is uniaxial compressive strength, b is carbide tip width, B is coal-rock brittleness index, k_1~k_4 is conical pick correlation coefficient, h is mean chip thickness, t is cutting-distances, k_{yj} is the ratio of mean contact stress and uniaxial compressive strength, β is conical pick installation angle, f' is cutting force correlation coefficient, A is coal-rock cutting impedance.

(2) Cutting Torque Analysis of the Cutting Head

The mean torque T can be expressed as follows:

$$T = n(D/2 + L)X_i, \tag{2}$$

where D is diameter of cutting head, n is the number of conical picks, L is distances from the cutting point to bottom of the pick-site.

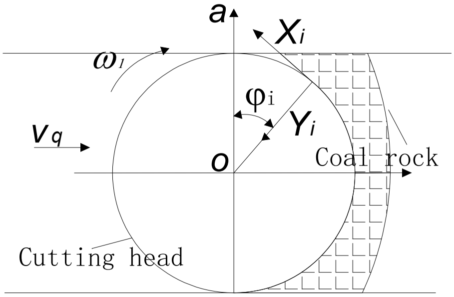
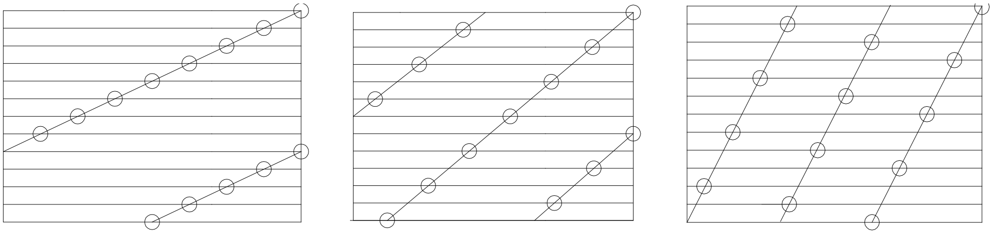


Fig. 2. Mechanical model of bolter miner cutting head

3. NUMERICAL MODEL

In order to select the optimum pick layout scheme. The 4 schemes of pick layouts are designed and make the performance evaluation by FEM. Pick layouts, divided into a single-sequence type, a double-checkerboard type, a hybrid type I, and see Fig. 3.



(a) Single-sequence type (b) Double-checkerboard type (c) Hybrid type I

Fig. 3. Different pick layouts of cutting head

The coal-rock material parameters were obtained by mechanical experiments, and the uniaxial compressive strength of coal-rock is 15 MPa. The coal-rock material parameters are shown in Table 1. The damage failure of coal-rock is composed of a main strain failure and a shear strain failure (Zhu 2015; Rauenzahn 1989). When the main strain failure or shear strain of the coal-rock reaches some point, some elements of the coal-rock will disappear automatically.

Table 1. Coal-rock material parameters

Parameter	Value
Angle of internal friction, °	52
Friction coefficient between pick and coal-rock	0.15
Friction angle between pick and coal-rock, °	8.53
Uniaxial compressive strength, MPa	15
Shear strength, MPa	1.4
Tensile strength, MPa	0.6

Table 2. Parameters of cutting head and coal-rock cutting

Parameter	Value
Pick layout	Single-sequence, Double-checkerboard, Hybrid type I
Traction speed, m/min	0.9
Rotational speed, r/min	20, 30, 40, 50

In practical, the rotational speed of cutting head is designed as a fixed value, which cannot be adjusted with the change of coal-rock strength in the process of coal-rock cutting. The traction speed of the cutting head can be automatically adjusted according to the coal-rock strength in the process of coal-rock cutting. Therefore, the same traction speed and different rotational speed are considered to carry on the simulation analysis of coal-rock cutting. The detailed parameters are shown in Table 2. The simulation model of single-sequence type is shown in Fig. 4.

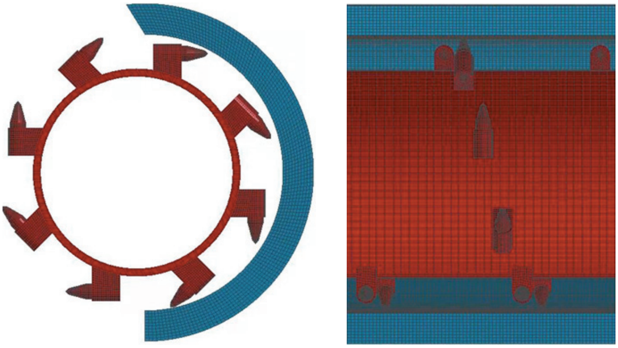


Fig. 4. Cutting coal-rock model of cutting head

4. RESULTS AND DISCUSSION

Three performance indexes were used to evaluate the performances of three different types of cutting head. The three indexes were proposed in previously published papers by Qiao et al. (2017b).

(1) **Load fluctuation coefficient**, δ_j: This reflects the degree of load fluctuation of the cutting head. The number of conical picks and the state of stress during cutting can change at any moment. Therefore, the load of the cutting head fluctuates within a circle. The load fluctuation coefficient indicates the degree of fluctuation of the cutting force, which is an important indicator measuring the reliability of the cutting head. The larger the value is, the stronger the load fluctuation. The model of the load fluctuation evaluation index is

$$\delta_j = \frac{1}{\overline{w}_j}\sqrt{\frac{\sum_{\varphi=1}^{N}\left(w_\varphi - \overline{w}_j\right)^2}{N}}, \tag{3}$$

where w_φ is the cutting force, $\overline{w}_j$ is the mean cutting force, and N is the sampling point for the cutting head.

(2) **Specific energy**, SE: This reflects the energy consumption when the cutting head cuts the unit volume of coal-rock, and is the key economic index for a bolter miner. The larger the value is, the greater the energy consumption and the lower the cutting efficiency. This is not only related to the physical properties of the coal-rock, but also to the pick configuration parameter and the cutting head movement parameter. The model of specific energy is

$$SE = \frac{\overline{w}_j L \rho}{M}, \tag{4}$$

where $\overline{w}_j$ is the mean cutting force (kN), L is the cutting length (mm), ρ is the density of the coal-rock, and M is the weight of the coal-rock (g).

(3) **Mean torque**, $\overline{T}$: This reflects an important characteristic of the cutting load, that is, the higher the mean value, the higher the load. There is a direct relationship among the strength of the coal-rock, the pick configuration, and pick layout parameters.

$$\overline{T} = \left(\sum_{k=1}^{n} T_n \right) / n, \tag{5}$$

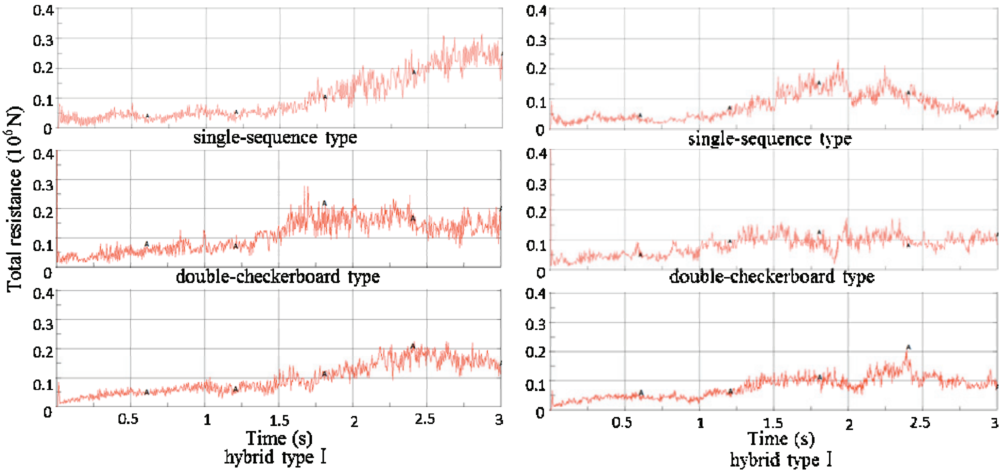
where n is the total number of data acquisitions, and T is the cutting torque.

As shown in Table 3, four sets of actual data are obtained. It can be seen from Table 3 that the load fluctuation coefficient are obviously different in different pick layout. As shown in Fig. 6, the load fluctuation coefficient of double-checkerboard is less than that of single-sequence and hybrid type I under the same distribution density of conical picks. And it is shown that the number of helical lines is not the decisive factor in determining the load fluctuation coefficient. The load fluctuation coefficient of double-checkerboard is relatively small because of the uniform circumferential distribution of conical picks. In addition, the load fluctuation coefficient of the sequential type is obviously more than that of the hybrid type I and chessboard type. That is because the number of conical picks of the sequential type contacting with coal-rock is more than that of the hybrid type I and chessboard type in the same time.

Table 3. The simulation value for different pick layout schemes

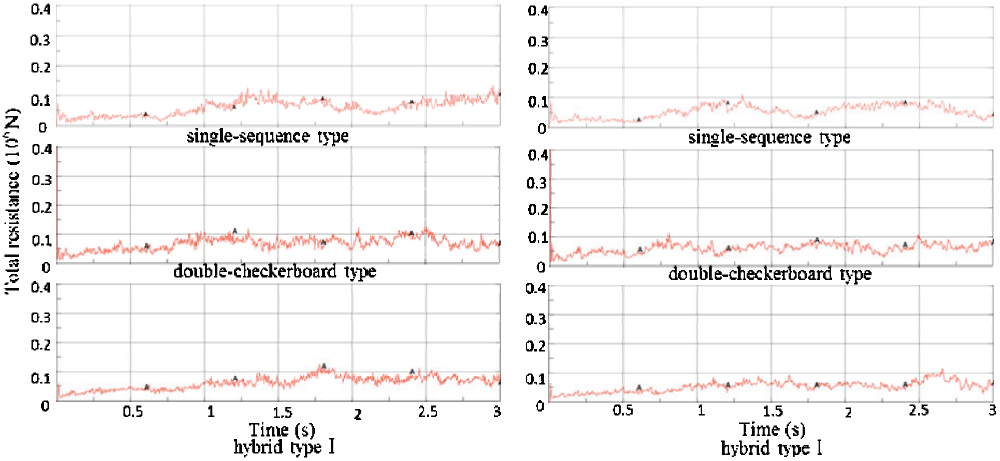
Rotational speed	Pick layout	$\overline{w}_j$ /N	$\overline{T}$ /N·m	δ_j	M/ρ (10^{-6}m^3)	SE (kW·h/m^3)
15	Single-sequence	104518	50691	0.5985	30519	2.8988
	Double-checkerboard	111225	53944	0.5181	29451	3.0039
	Hybrid type I	96519	46812	0.5540	28374	2.8792
20	Single-sequence	66905	32449	0.5000	21572	2.6251
	Double-checkerboard	78918	38275	0.4675	21392	2.8769
	Hybrid type I	62970	30541	0.4890	20362	2.6177
25	Single-sequence	49133	23830	0.3989	17385	2.3922
	Double-checkerboard	67363	32671	0.3673	17572	2.8446
	Hybrid type I	45484	22060	0.3678	16383	2.3499
30	Single-sequence	41621	20186	0.3616	15067	2.3381
	Double-checkerboard	61209	29686	0.3412	15564	2.7629
	Hybrid type I	41967	20354	0.3095	14360	2.3237

As shown in Fig. 5, it can be seen that the load parameters of cutting head by different pick layouts, but at same traction speed, same rotational speed and same diameter of cutting head. As shown in Fig. 7, the cutting torque decreases linearly with the increase of the rotational speed from 20 to 40 r/min, and the cutting torque tends to be relatively stable when the rotational speed increases from 40 to 50 r/min. However, the cutting torque of the hybrid type II varies greatly because of its large transversal distance. At the same rotational speed, the relationship of mean torque among the three pick layouts is as follows: double-checkerboard > single-sequence > hybrid type I. Therefore, the smaller the distribution density of conical picks, the smaller the cutting torque of cutting heads. Under the same distribution density of conical picks, the cutting torque of double-checkerboard is obviously larger than that of single-sequence and hybrid type I, and the cutting torque of hybrid type I is a little smaller than the single-sequence.



(a) Working condition 1

(b) Working condition 2



(c) Working condition 3

(d) Working condition 4

Fig. 5. Total resistance curves of different cutting heads

As shown in Fig. 8, the specific energy decreases with the increase of rotational speed, which is due to the fact that the volume of broken coal-rock and the cutting torque increase at the same time, and the rate of reduction of coal- rock volume is lower than that of cutting torque. According to the relationship between specific energy and the pick layout, the specific energy of double-checkerboard is relatively high and the efficiency of coal-rock cutting is the lowest than the other two. In terms of specific energy, there is no difference between single-sequence and hybrid type I, and the maximum value is not exceeding 5.5%.

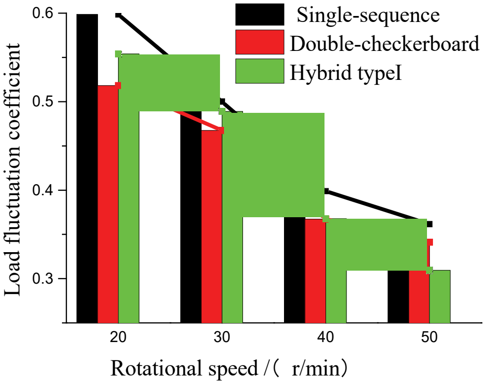


Fig. 6. Load fluctuation coefficient of cutting head

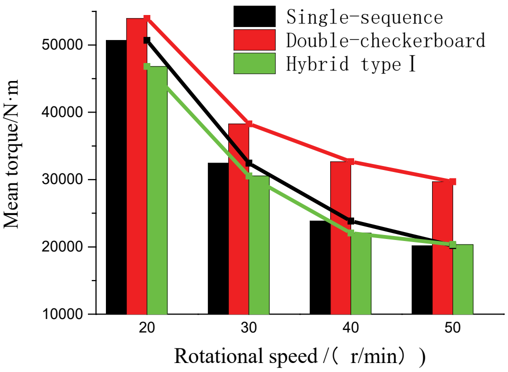


Fig. 7. Mean torque of cutting head

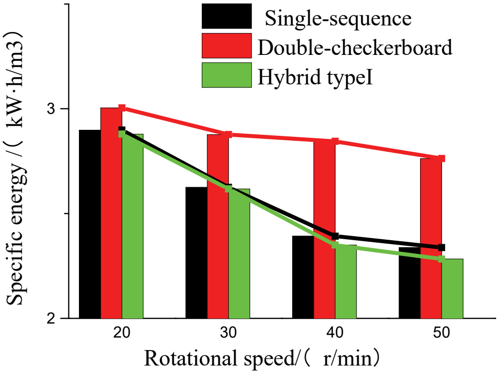


Fig. 8. Relationship between specific energy and rotational speed

5. EXPERIMENTAL VERIFICATION AND APPLICATION

5.1. EXPERIMENTAL EQUIPMENT

According to the similarity theory, a coal-rock cutting equipment has been developed with a single-sequence type. And a series of cutting experiments by the cutting head were conducted with cutting machine (see Fig. 9). The experimental parameters are the same as those of simulation. And the rotational speed is 20, 30, 40 and 50 r/min, respectively.

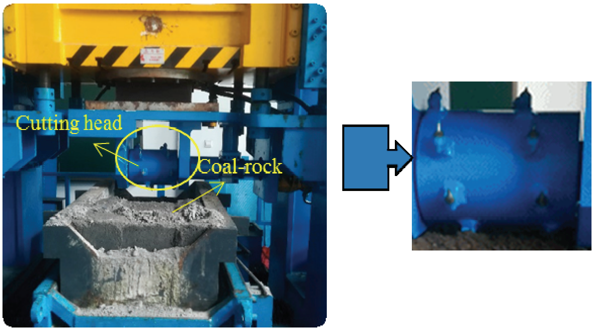
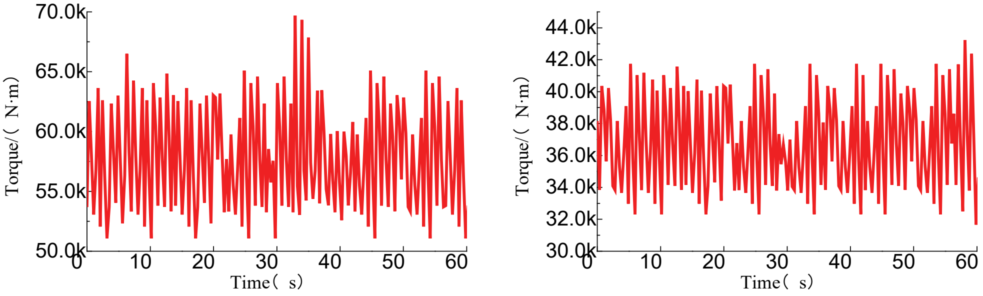


Fig. 9. Cutting machine of single-sequence type

5.2. DATA TREATMENT AND RESULT ANALYSIS

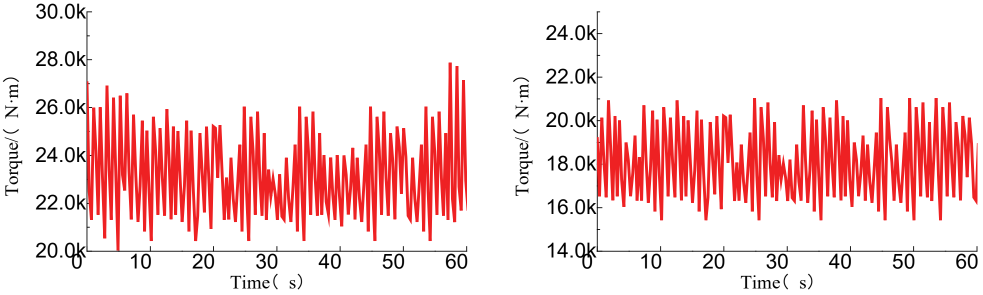
Figure 10 is the fracture zone formed on the surface of the coal-rock. It can be seen that the fragmentation of coal-rock is relatively uniform when the cutting head with a single-sequence type breaks the coal-rock. It has no coal-ridges formed on the surface of the coal-rock, and the effect of coal-rock cutting is good.

Fig. 10. The fracture zone formed on the surface of the coal-rock



(a) Working condition 1

(b) Working condition 2



(c) Working condition 3

(d) Working condition 4

Fig. 11. Torque curves under different working conditions

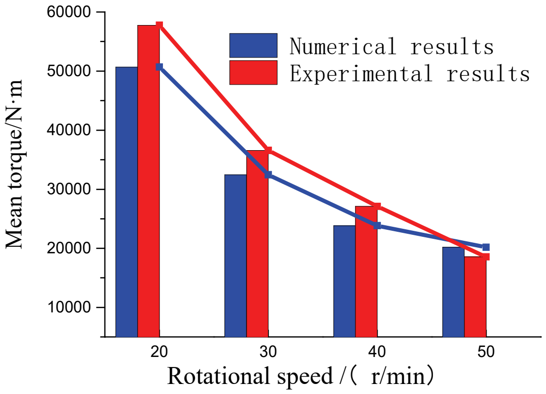
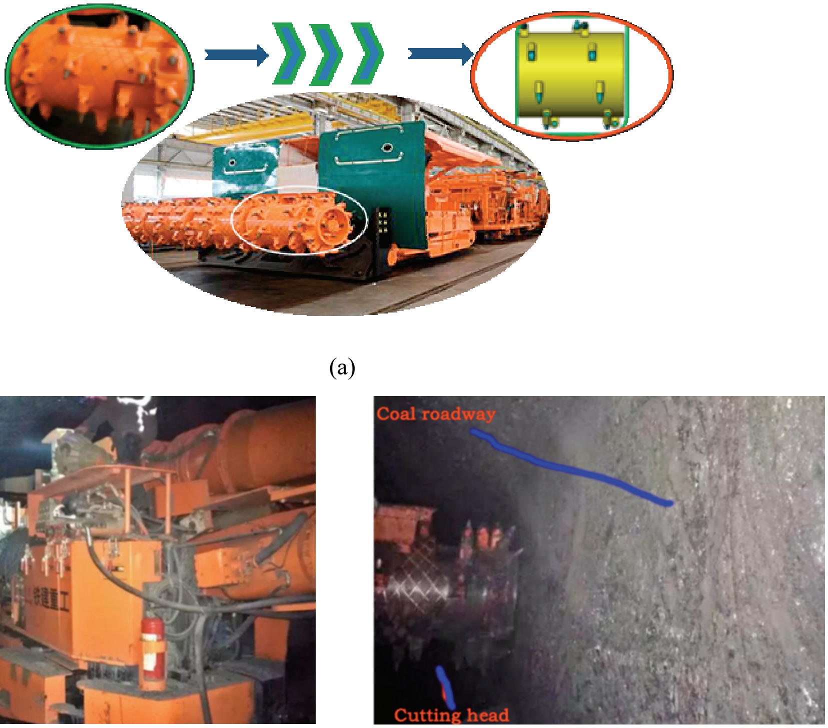


Fig. 12. Relation between mean torque and rotational speed

As shown in Fig. 11, it can be seen that the torque is different under different working conditions. The simulation value of mean torque is shown in Fig. 7. As shown in Fig. 12, in order to compare mean torque from the numerical simulations and cutting experiments, the mean torque of cutting head was obtained. According to similarity theory, the mean torque values are close between two datasets as the range of rotational speed from 20 to 50 r/ min. And the mean torque values obtained from the cutting experiments are only a little larger than that from numerical simulation as the range of rotational speed from 20 to 40 r/ min. It can be explained that the simulation is carried out under an ideal condition, and the uncontrollable factors are increased with the increase of rotational speed. Such as, the testing system is subjected to many external disturbances, like the heterogeneity of coal-rock. The maximum deviation between the simulation value and the test value is 14.0%, and the deviation is within a reasonable range, which verifies the correctness of the simulation model.

5.3. APPLICATION RESULTS

The bolter miner was operated in some coalmine, and it achieved the expected results. The coal-rock material parameters are listed in Table 1. The cutting head is connected by four small drums, each with a single-sequence type. Figure 13(a) shows the shape of cutting head and the whole machine of bolter miner.



(a)

(b)

(c)

Fig. 13. Bolter miner cutting head used in some coalmine

As shown in Fig. 13(b) and 13(c), the advancing speed can be adjusted for the whole load in the actual excavation, and the actual operating speed of the machinery does not exceed 8 m/min. The maximum day rate of the bolter miner is more than 130 meters, and it fully meets the design requirements. The application results further verify the rationality of simulation and experiment.

6. CONCLUSIONS

In this research, three simulation models of different cutting heads were established, and the whole crushing process of coal-rock was simulated by FEM. The factors affecting the cutting effect were considered, such as the load fluctuation coefficient, mean torque, and specific energy. The results show that the relationship of load fluctuation coefficient among the three pick layouts is as follows: sequential type > hybrid type I > checkerboard type. The circumferential pick layouts can reduce the load fluctuation coefficient of cutting head. At the same rotational speed, the relationship of mean torque among the three pick layouts is as follows: double-checkerboard > single--sequence > hybrid type I. Therefore, the smaller the distribution density of conical picks, the smaller the cutting torque of cutting heads. Under the same distribution density of conical picks, the cutting torque of double-checkerboard is obviously larger than that of single-sequence and hybrid type I, and the cutting torque of hybrid type I is a little smaller than the single-sequence. In terms of specific energy, there is no difference between single-sequence and hybrid type I, and the maximum value is not exceeding 5.5%. At last, the reality of the simulation is verified by cutting experiments and application. The results of this study have been successfully applied to the development of the first shield-type bolter miner in China.

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