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FINITE ELEMENT ANALYSIS OF LOAD CHARACTERISTIC OF SHIELD BOLTER MINER CUTTING HEAD UNDER COMPLEX COAL SEAM CONDITION

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Abstract. Aiming at the complex conditions of the first shielded bolter miner in the actual work, the mechanical model of bolter miner cutting head was established. Based on cutting mechanism of the conical pick and the cutting head, the cutting head load and torque analysis model under complex coal seam were established. The dynamic characteristics of load and torque in the process of cutting head are analyzed under three different working conditions of cutting roof-coal layers, coal-floor layers and coal seam by finite element method. The results show that when the damage variable D = 1, the coal-rock completely lacks the bearing capacity, and it forms arc-shaped crushing groove on the coal-rock. The large difference of torque between roof-coal layers and the roof-coal layers in the conical pick is 112 Nm, which indicates that the cutting head has the best performance with cutting the coal seam first and then cutting the rock. In the process of excavation, the load fluctuation coefficient of cutting the coal-floor layers and roof-coal layers is about 1.2 times of that of the coal seam. The results can provide a reference for the efficient cutting and performance evaluation of the bolter miner.

Keywords*: complex coal seam, shield bolter miner, load characteristic, specific energy, load fluctuation*

INTRODUCTION

Mining and supporting are the two core processes of coal mine production(J.S. Jang et al., 2016; Q.Q. Zhang et al., 2016). Shield bolter miner is a complete set of equipment to achieve synchronous construction between the excavation and bolting-mesh support. Cutting coal-rock is accomplished by its front swingable cutting head,

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and bolt supporting is accomplished by bolting machine installed at the rear of the bolter miner, which gained widely attention by the engineering as soon as it came out.

In May 1991, the Tahmoo Coal Mine in Australia first realized synchronous construction of excavation and support, which marks a birth of the world's first bolter miner (Bertignoll et al., 1995).Since then, bolter miner began to be used in the United States, South Africa, Australia and other countries, and it has achieved good effect (Vierhaus et al., 2002; Leeming et al., 2001; Mogk, et al., 2002). Until the beginning of twenty-first Century, a bolter miner was applied to coal lane tunneling in China, but the progress is not great. At present, the research on bolter miner is still in a preliminary stage, and the information available for reference is very limited. Because of the principle of mucking and collection is different from that of shearer, the structure of cutting head between bolter miner and shearer is very different, but there are some similarities between the two machines in the pick layout and the track of movement (S. Yasar et al., 2017; W. Shao et al., 2017;C. Balci et al., 2007; N. Bilgin et al., 2006). Therefore, the cutting performance of bolter miner cutting head can be studied by using some mature methods in shearer. The relation among pick layout and drum load, rotating speed, traction speed were obtained by establishing the mathematical model of load fluctuation (C.L. Du et al., 2008). The drum load system was developed by finite element software, and successfully applied to shearer (X.H. Li et al.,2016). And the Markov model was used to track the coal interface effectively, allowing the shearer to cut more coal seams and less rock (W. Li et al., 2014).

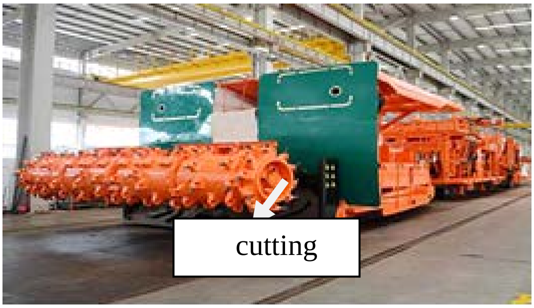


Fig. 1. The first shield bolter miner in China

In conclusion, the research on bolter miner of our country starts relatively late in comparison with coal developed countries. The domestic scholars have done some research on the characteristics of shearer cutting coal-rock, but there is no literature to study the bolter miner’s cutting characteristic now. It is necessary to improve and perfect the relevant technology in this field. In view of this, as shown in Figure 1, this paper takes the first shield bolter miner cutting head in China as the research object to simulate coal-rock failure process by finite element method(S.A. Heydarshahy and S. Karekal, 2017; W.J. Yu et al., 2014; T. Xu et al., 2015; Y.M. Xia et al., 2011). Also, it analyzes the load characteristics of an conical pick and cutting head under different working conditions, which provides the theoretical basis for the research and development of the bolter miner.

MECHANICAL MODEL OF BOLTER MINER CUTTING HEAD

COAL-ROCK BREAKAGE MECHANISM

Bolter miner cutting head is composed of the drum, pick-sites and conical picks. Different from traditional shearer and roadheader, the cutting head does not have the helical vane, so the pick-sites are directly welded to the cutting head. The falling coal is transported to the belt conveyor through the front scraper impeller. And the shearer's pick-site are welded on the helical vane, relying on the helical vane to throw the falling coal into the scraper conveyor and send away. To a certain degree, shearer limits coal fragmental size in contrast with bolter miner. And the different structure leads a big difference between bolter miner cutting head and shearer helical drum in mechanical properties.

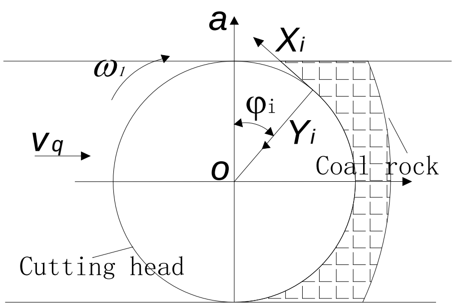


Fig. 2. Mechanical model of bolter miner cutting head

The movement of cutting head is the synthesis of the drum rotation and the traction motion of bolter miner, and the crushing of coal-rock is accomplished by the rotation of different numbers of picks. As shown in Figure 2, the force of cutting head can be divided into cutting force X_i, traction force Y_i and axial force Z_i.

CUTTING FORCE ANALYSIS OF THE CONICAL PICK

The cutting force X_i is calculated as follows:

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

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

CUTTING TORQUE ANALYSIS OF THE CUTTING HEAD

The mean torque T is calculated as follows:

$$T = n\left(\frac{D}{2} + L\right)X_i \tag{2}$$

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

JUDGMENT CRITERIA AND CONSTITUTIVE RELATION OF COAL-ROCK

It is shown coal-rock under the loading is in elastoplastic properties(Y.J. Yang et al., 2015; D.K. Wang et al., 2010), so the Druker-Prager elastoplastic constitutive model is used to describe the strength characteristics of coal-rock. The model can be presented as follows:

$$\alpha I_1 \sqrt{J_2} = K_f \tag{3}$$

$$\alpha = \frac{\sin\varphi}{\sqrt{9 + 3\sin^2\varphi}} \tag{4}$$

$$K_f = \frac{3c\sin\varphi}{\sqrt{9 + 3\sin^2\varphi}} \tag{5}$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_x + \sigma_y + \sigma_z \tag{6}$$

$$J_2 = \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \tag{7}$$

where, c is cohesive force, φ is friction angel, α and K_f is related to c and φ, I_1 is the first invariant of stress tensor, J_2 is the second invariant of stress tensor, σ_1 is maximum principal stress, σ_2 is intermediate principal stress, σ_3 is minimum principal stress.

In this paper, the damage model is used to clarify the coal-rock failure process(X.H. Zhu and H. Li, 2015). According to the coal-rock breakage Mechanism, the critical point of coal-rock unstable failure is point C as shown in Fig. 3. And the failure process can be described as three stages: the elastic deformation stage AB, the plastic deformation to the failure stage *BC*, and the post failure stage *CD*.

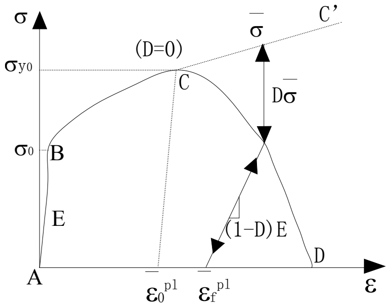


Fig. 3. Stress-strain curve with progressive damage degradation

The plastic deformation is calculated as follows:

$$\omega_s = \int \frac{d\bar{\varepsilon}^{\rho l}}{\bar{\varepsilon}_s^{\rho l}(\theta_s, \dot{\bar{\varepsilon}}^{\rho l})} \tag{8}$$

where, $\bar{\varepsilon}_s^{\rho l}$ is pre-plastic-strain, $\dot{\bar{\varepsilon}}^{\rho l}$ is strain rate, θ_s is shear stress ratio.

In the case of $\omega_s = 1$, the coal-rock is at point *C*, and then the coal- rock are gradually unstable.

In order to describe the coal-rock damage state, the stress tensor σ is used to be represented the stress state, the stress tensor of coal-rock can be expressed by Eq (7).

$$\sigma = (1 - D)\ \bar{\sigma} \tag{9}$$

where, $\bar{\sigma}$ is stress tensor, *D* is damage variable.

It can be concluded when damage variable *D* = 1, the falling coal-rock is disappeared from the model**.**

NUMERICAL MODEL

As shown in Figure 4, during the formation of coal seam, the roof and floor are formed at the same time, which are located in the upper and lower of coal seam respectively, and their hardness is generally greater than the coal seam(J.Q. Jiang and J. Dai, 2013). According to the actual working environment, three cutting models of coal seam, roof–coal layers, coal-floor layers are established. The finite element model of bolter miner cutting roof-coal layers is showed in Figure 5. The bottom of coal-rock is adopted the non-reflecting boundary, and the contact method of penalty function is used for conical and coal-rock.

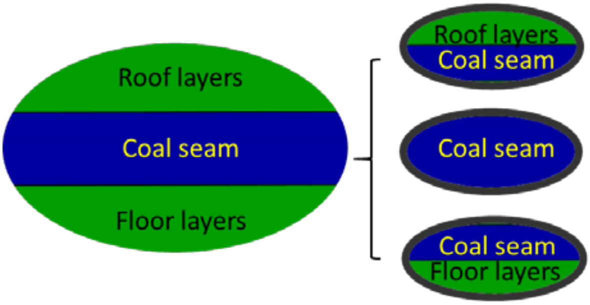


Fig. 4. Three working conditions of cutting head

Assuming that the roof and floor are the same rock. The compressive strength of coal is 20 MPa, and the compressive strength of rock is 30 MPa, the relevant parameters of cutting head and coal-rock are shown in Table 1.

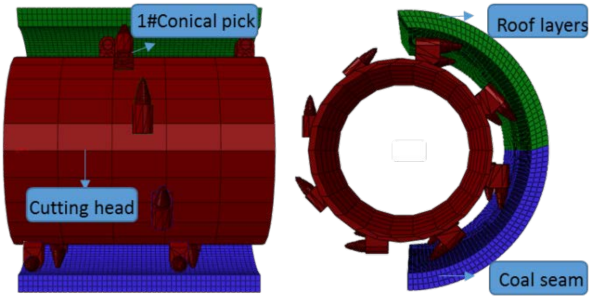


Fig. 5. The model of cutting roof-coal layers

Table 1. Material parameter

Material	Elastic modulus (MPa)	Poisson ratio	Density (kg/m^3)	Uniaxial compressive strength (MPa)
Cutting head	210000	0.3	7800	—
Coal seam	3500	0.3	1500	20
Rock stratum	7316	0.32	2500	30

RESULTS AND DISCUSSION

FAILURE ANALYSIS OF COAL-ROCK

As shown in Figure 3, the interface between fore-pick and coal-rock produces elastic deformation (Line AB) during the initial stage of excavation, and then gradually produces plastic deformation with the increase of coal-rock stress (Point B). As shown in Figure 6(a), the interface between picks and coal-rock is gradually damaged. When the damage variable D=1(Point D), coal-rock completely lacks the bearing capacity. At this time, the stress state of coal-rock is determined by Eq.(9).

As shown in Figure 6(b)-(d), the damage area of coal-rock is gradually increasing. A piece of fracture belt comes into being on the interface between the fore-pick and coal-rock. The rear pick will cut coal at the same time, and fracture belt produced by fore-pick and rear pick will be merged together in the end.

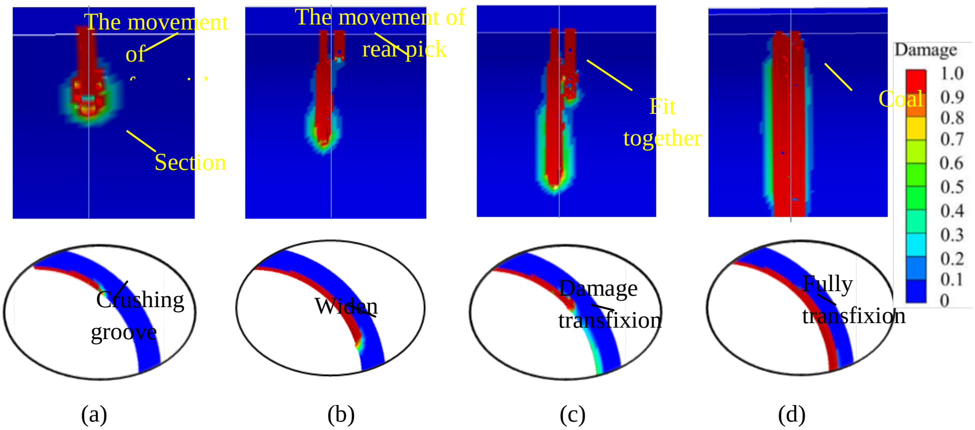


Fig. 6. Crushing process of coal-rock

CONICAL PICK CUTTING PERFORMANCE

Conical pick 1# is the research object in Figure 5. In the case that the conical pick is rotated for a circle, cutting force and traction force are as shown in Figure 8 during cutting roof-coal layers. It can be concluded that the force of X_i and Y_i increase rapidly. The reason is that coal-rock has a great impact on the conical pick, causing the load to increase suddenly. When the conical pick turns to cut the coal seam, the force of X_i and Y_i decrease rapidly by 25% and 15%. The reason is that the hardness of coal seam is lower than roof layers. On the contrary, the load of conical pick will suddenly increase at the critical interface on cutting floor-coal layers.

As shown in Table 2, the mean torque value and standard deviation of cutting roof layers are greater than the value of cutting floor layers. The torque difference of cutting the roof-coal layers is larger than that of the coal-floor layers which is 112N m. As shown in Figure 8, the torque descending rate of cutting roof-coal layers faster than the rising rate of cutting coal-floor layers, which indicates less impact of cutting head from cutting coal seam to the floor layers, but the impact of cutting roof-coal layers on the conical pick is great. As shown in Figure 9, the descending rate under the roof-coal layers condition is faster than the rising rate under the roof-coal layers condition. It is indicated that the impact of the cutting head is smaller when the transition from the coal seam to the floor layers.

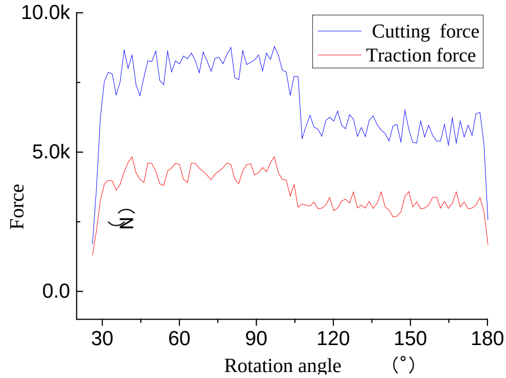


Fig. 8. Force curve of a pick cutting roof and coal

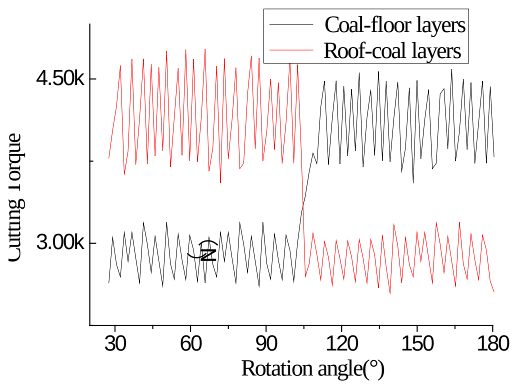


Fig. 9. Cutting torque variation curve

Therefore, it can be concluded that the cutting force of rock stratum on the cutting head is relatively larger than the cutting force of coal seam. In order to reduce the impact of the load, the cutting head should cut coal seam first and then rock stratum.

Table 2. Torque statistics of a conical pick cutting coal-rock

Condition	Name	Mean value (N·m)	Standard deviation	Maximal value (N·m)	Difference value (N·m)
A	Coal	2892	70	3206	—
B	Floor	4059	75	4590	1175
	Coal	2884	68	3192	
C	Roof	4165	78	4773	1287
	Coal	2878	67	3290	

The specific energy is a common index to reflect the cutting efficiency of the cutting head. The higher the energy is, the more energy is needed for cutting the same volume of coal-rock, and it means that the cutting efficiency is lower. The specific energy is calculated as follows:

$$SE = \frac{W}{V} = \frac{\overline{T}tn}{9550 \times 3600V} \tag{10}$$

where, SE is specific energy (k W h/m^3), V is cutting volume (m^3), n is rotational speed (r/min) ; t is cutting time (s).

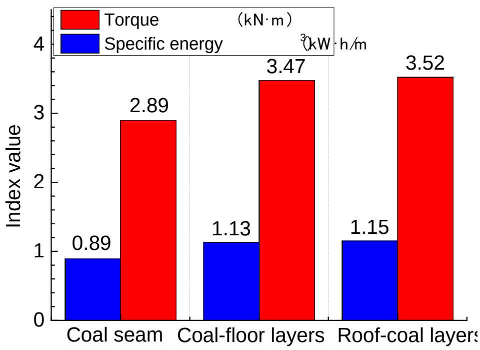


Fig. 10. The variation of torque and specific energy

The relationship between specific energy and the conical pick under different working conditons is shown in Figure 10. It shows that the specific energy of cutting coal seam is about 23% less than cutting roof-coal. The specific energy of the three working conditons are in the following order C>B>A, which is same as the relationship of torque magnitude for each working condition. It needs higher energy to cut rock stratum first and then cut the coal seam. Therefore, from the two indexes of specific energy and torque, the cutting head should cut coal seam first and then rock stratum.

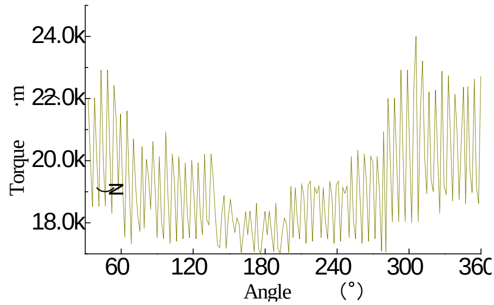
CUTTING HEAD CUTTING PERFORMANCE

Based on the study of cutting effect under coal-rock layers conditions in different orders, it shows that the impact of cutting rock stratum first is larger than cutting coal seam first. However, the load fluctuation has different effects on cutting head when it simultaneously cuts coal seam and rock stratum under actual working condition, compared with cutting coal-rock layers in proper order.

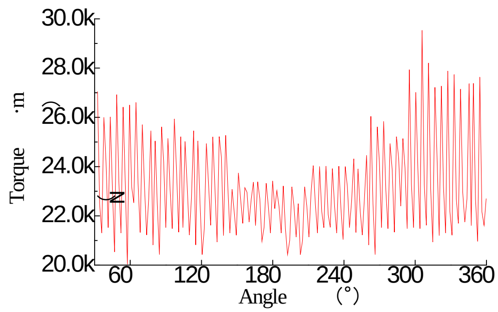
The number of cutting picks during the cutting head rotation will cause the load fluctuation of the cutting head. In this section, it mainly considers the impact on load fluctuation when cutting complex coal seam, and uses the fluctuation coefficient to express the load fluctuation. The load fluctuation coefficient is calculated as follows:

$$\delta_j = \frac{1}{\bar{w}_j}\sqrt{\frac{\sum_{\varphi=1}^{N}\left(w_\varphi - \bar{w}_j\right)^2}{N}} \tag{11}$$

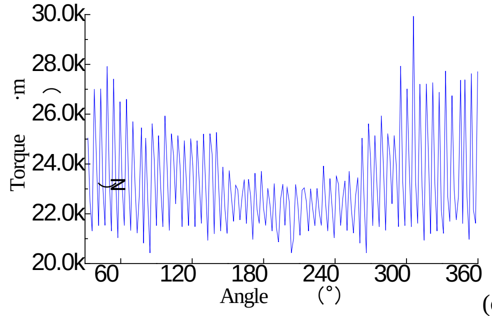
where, δ_j is load fluctuation coefficient, w_φ is cutting force, $\bar{w}_j$ is mean cutting force, N is the number of samples.



(a) Coal seam



(b) Coal-floor



(c) Roof-coal

Fig. 11. Torque variation curve of cutting head

As shown in Figure 12, the load fluctuation range of cutting head under the roof-coal layers and the coal-floor layers conditions is large, the fluctuation coefficient is about 1.2 times than cutting the coal seam, which is due to the physical properties of coal and rock. The load fluctuation coefficient of cutting head under the coal-floor layers and roof-coal layers conditions is similar. Because there are picks cutting coal seam and rock stratum at the same time, the overall load varies little. As shown in Figure 11 and Figure 12, from the cutting torque value, the mean torque value of cutting roof-coal and coal-floor is larger than the value of cutting coal seam. That's because the roof layers and floor layers are harder than coal seam. Also, the mean torque value between cutting roof-coal and cutting coal-floor has not varied distinctly.

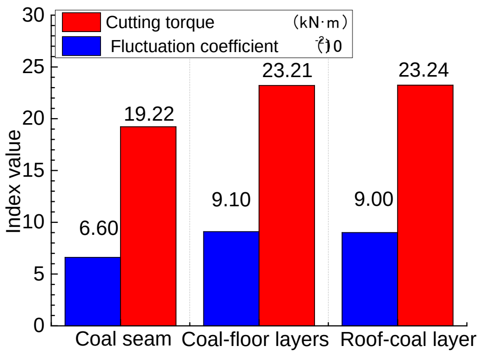


Fig. 12. The variation of torque and load fluctuation coefficient

CONCLUSION

Through the simulation models of coal-rock failure are established under three different working conditions, the crushing process of coal-rock is discussed, and the load characteristic of a conical pick and the cutting head are obtained under complex coal seam condition. The main conclusions are as follows:

(1) Coal-rock completely lacks the bearing capacity when the damage variable is D = 1, and it forms the arc-shaped crushing groove on the coal-rock.

(2) Torque and specific energy of an conical pick cutting roof-coal are higher than that of cutting floor-coal, which indicates that the cutting head has a greater impact and the cutting efficiency is lower under roof-coal layers condition. In order to improve service life of the cutting head, it can cut coal seam first and then rock stratum.

(3) The load distribution of cutting head is different under complex coal seam condition. The load fluctuation of cutting head is similar under roof coal and floor coal conditions, which is greater than the cutting head under coal seam condition. All these will provide a theoretical guidance for the construction of bolter miner.

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