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NUMERICAL SIMULATION ANALYSIS OF ROCK BREAKING OF CUTTING PART OF ROADHEADER WITH A TRANSVERSE HEAD UNDER DIFFERENT DESIGN PARAMETERS

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Abstract: In order to analyze the impact angle of pick cutter, the angle of alloy head and the cutting line spacing on rock breaking effect, the three-dimensional model of rock cutting by pick cutter was established by solidworks, and the three-dimensional finite element model of rock breaking by pick cutter based on penetration failure and compression damage was established by using dynamic simulation software ANSYS/LS-DYNA. For the drum with a diameter of 1200 mm, a length of 900 mm and a rotational speed of 30 rot/min, when the impact angles of the picks are 30°, 37°, 45° and 52°, the angles of the alloy heads are 70°, 80°, 90° and 100°, and the intercept distances are 250 mm, 275 mm, 300 mm and 325 mm, the rock breaking simulation based on the finite element analysis software is carried out, and the load and specific energy consumption of the drum are obtained. Finally, through the analysis and comparison, the existing parameters are optimized, and a better parameter model is obtained.

Keywords**:** *roadheader with a transverse head, cutting head, cutting tooth, specific energy consumption, cutting load*

1. INTRODUCTION

Roadheaders are the main machines driving in tunnels, bridges, subways, coal mines and other projects. They play an important role in all aspects of the national economy.

Combined with the theoretical knowledge of rock breaking and the cutting law of the pick, strengthen and manufacture the specific parts of the roadheader, improve the

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cutting ability of the pick, prolong the service life and improve the crushing efficiency of the roadheader, which will bring greater benefits to the mining of coal and rock mining companies. The ability of picks to cut coal and rock is a basic component of the cutting mechanism of roadheader. It is of great value and practical significance to study the ability of cutting coal and rock.

At present, the mining height of coal mining face is gradually increasing, the mining technology and mining equipment are developing (Dolipski et al. 2017), and the roadway rock excavation speed is accelerating (Miao et al. 2015). The rock roadway excavation equipment is mainly cantilever roadheader (Liu 2021), and the pick bears large impact load in the cutting process (Xu 2021). Therefore, the pick is the most easily worn and damaged component, which will affect the working performance of the whole roadheader (Cheluszka 2020). In order to improve the working efficiency of roadheader, many scholars (Zhang et al. 2021; Comakli 2019) at home and abroad have done a lot of research (Liu et al. 2017; Kolesnichenko et al. 2017) on the cutting mechanism and performance of pick. Using ANSYS/LS-DYNA, Du et al. analyzed the stress of the pick at different cutting line speeds, and concluded that with the increase of cutting speed, the maximum peak stress on the pick gradually decreased, and with the continuous increase of linear speed, the decrease range of the maximum peak stress decreased (Du et al. 2013). Li et al. studied Effects of Spiral Line for Pick Arrangement on Boom Type Roadheader Cutting Load (Li et al. 2016). Jian Ping Li research team took cutting specific consumption as the optimization goal, and cutting picks of spatial parameters as the design variables, and then established the optimization mathematical model of the arrangement of cutting picks. Mathematic model was solved by Matlab programming, then got the optimized arrangement parameters of cutting picks. According to the optimized parameters, manufactured the aiguilles and carried out the drilling test. The result indicated that production efficiency and advance speed of optimal designed aiguilles were all improved, abrasion of cutting picks were roughly the same and there was no clear cut mark on the drilling holes (Li et al. 2011). Chang-long Du research team studied the pick arrangement of shearer drum based on load fluctuation. The effects of pick arrangements (including punnett square, sequence, aberrance I and II) on the drum load fluctuation coefficient are discussed (Du et al. 2008). The Songyong Liu team studied the influence of the working angle of the cutting tooth on the cutting performance of the cutting head (Liu et al. 2017). The Zhang Mengqi team studied a new method for the layout of the cutting tooth of the roadheader based on the spatial position of the meshing cutting tooth and the verification of the cutting rock (Mengqi et al. 2021).

In the above study, a variety of mechanical models of coal and rock fragmentation were established, and the influence of some cutting parameters on the cutting performance was analyzed in detail. However, there is insufficient research on numerical simulation analysis of rock breaking under the action of different impact angles of picks, angles of alloy heads, and intercept spacing in the process of rock breaking with picks, and there is less research on numerical simulation of rock breaking with 3D finite element method. Therefore, based on the above research, this paper obtains the characteristic curves of drum load and specific energy consumption based on the rock breaking simulation of finite element analysis software. Finally, through the analysis and comparison, the existing parameters are optimized, and a better parameter model is obtained, which provides a theoretical basis for later research.

2. INTRODUCTION OF CUTTING UNIT STRUCTURE

The cutting part is mainly composed of five parts: cutting head, gear, cutting motor, cutting guard plate and base. The cutting head is the core part of the whole cutting part, and it is also an important part that can best embody the cutting performance of the roadheader in this paper. It directly affects the service life and cutting efficiency of the cutting part in this paper. Therefore, this paper will focus on the research of the cutting head in this paper.

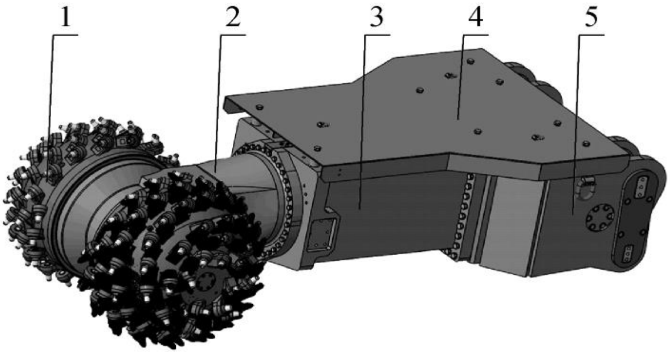


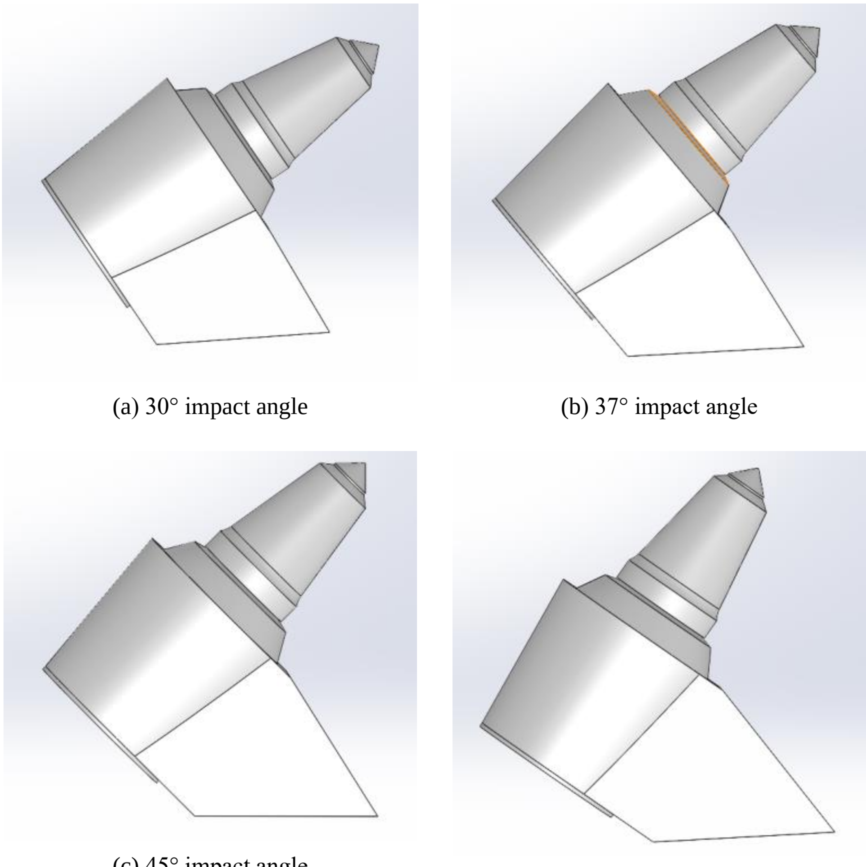
Fig. 1. Structure diagram of cutting part:
1 – cutting head, 2 – gear, 3 – cutting motor; 4 – cutting guard plate, 5 – seat

3. INTRODUCTION OF PICK ARRANGEMENT PARAMETERS

This paper mainly changes the parameters of the impact angle of the pick, the angle of the alloy head and the intercept distance of the pick, and explores the influence of the pick on the rock breaking effect. When different installation angles cut into the rock, the stress will be different. The angle of the alloy head and the intercept distance affect the area of rock breaking and the degree of rock fragmentation. At the same time, they will also affect the force of the single pick, thereby affecting the service life of the pick.

3.1. IMPACT ANGLE OF PICKS

The impact angle is the angle between the motion trajectory of the pick tooth and the central axis of the pick tooth. According to the survey, the installation angle of the pick is generally between 30° and 60°, so this paper designs four groups of data of 30°, 37°, 45° and 52° for analysis.



(a) 30° impact angle (b) 37° impact angle

(c) 45° impact angle (d) 52° impact angle

Fig. 2. Impact angle and tooth base assembly of each group of picks

The impact angle will affect the cutting angle of the pick. When the impact angle is larger, the resistance of the pick will be greater, and the cutting efficiency will be improved. In theory, it is necessary to improve the cutting angle of the pick as far as possible to ensure the strength of the pick. Therefore, this paper will simulate and analyze these groups of data, so as to obtain the most suitable impact angle interval and improve the efficiency of the pick.

3.2. ANGLE OF ALLOY HEAD

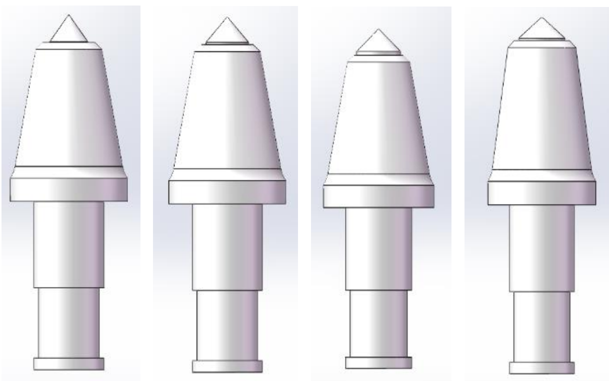
The angle of the alloy head of the pick has a great influence on the pick. The greater the cone angle is, the greater the resistance is, and it will be difficult to break the rock. However, if the cone angle is too small, it will also affect the stress at the front end of the pick, leading to the pick being more prone to fracture and affecting the service life of the pick. Therefore, a suitable cone angle is very important for the pick.

Generally speaking, the angle of the alloy is between 60° and 100°. In order to study the influence of the angle between the alloy head of the pick on the performance of the pick in this paper, four different cone angles are designed for simulation, and the U82 type pick with the cone angle of the alloy head between 70° and 100° is studied.

Table 1. Parameters of the angle of each alloy head

Model	Alloy cone angle [°]	Alloy head diameter [mm]	Tool diameter [mm]	Length of handle [mm]
1	70	30	80	72
2	80	30	80	72
3	90	30	80	72
4	100	30	80	72

Since the mesh generation of ANSYS will be used in the following part of this paper, it is necessary to re-model each parameter. The parameters in Table 1 are used to model and assemble each pick into the same tooth base and drum for simulation analysis to study the influence of alloy cone angle.



(a) 70° (b) 80° (c) 90° (d) 100°

Fig. 3. The picks of the angle of each alloy head

3.3. TOOTH SPACING

The intercept line spacing is the distance between the two intercept teeth along the same spiral line of the drum. The smaller the intercept is, the denser the distribution of picks will be, and the rock will be broken more thoroughly in the process of rock breaking. However, the more dust will be generated at the same time, and the power allocated by a single pick will be lower, resulting in waste. The larger the cutting line spacing, the more sparse the pick distribution, the greater the resistance of the single pick, and the cutting efficiency will be reduced. If more than two spirals are distributed on the cutting head, the number of teeth on each spiral is $(z - 2)\ n$, where n is the number of spirals. n spirals are distributed throughout the cutting head, that is, the cutting line spacing between adjacent picks on the same spiral is $Ln\ (z - 3)$. Therefore, the appropriate intercept spacing is very necessary. According to the literature, this paper selects 250 mm, 275 mm, 300 mm, 325 mm four groups of intercept spacing for experimental comparison.

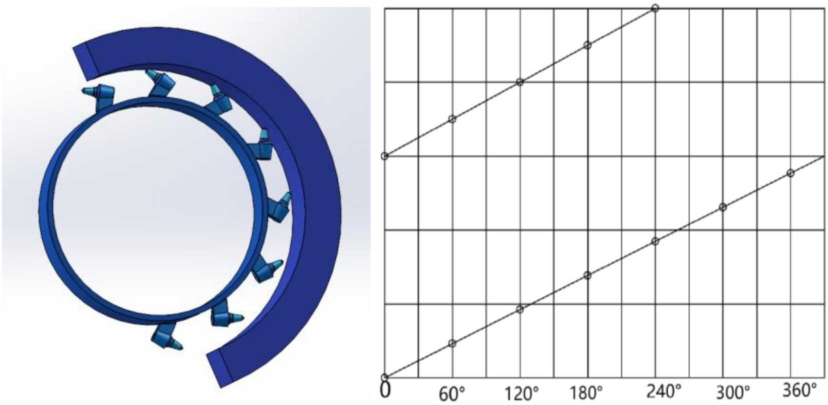


Fig. 4. Simplified drum model and profile expansion of picks

4. DETERMINATION OF DRUM PARAMETERS

The size and rotational speed of the drum can affect the cutting process in this paper. The larger the drum is, the more the rock volume removed by rolling for one week is, but the resistance is also greater. Therefore, the appropriate size of the drum is very important. It can improve the work efficiency of cutting, and can cooperate with the force of cutting teeth, improve the service life of machinery. According to the market investigation and literature review, this paper adopts a drum with a diameter of 1200 mm and a length of 900 mm. According to previous experience and related literature, the speed of this paper is set at 30 r/min.

5. INTRODUCTION OF ROCK PROPERTIES PARAMETERS

When selecting the type of roadheader with a transverse head, it is necessary to consider the rock properties in the specific situation, because the cutting head in this paper will have different performance in the face of different rock strength, and different rocks will have some different strength. For example, the density of rock, compressive tensile strength and so on, these will affect the performance of cutting rock in this paper. This paper mainly simulates and tests the rock with compressive strength of 9 MPa. Here are the specific values of the rock required in this article.

Table 2. Rock material parameters

G	S_{max}	A	B	C	N	D_1	D_2	K_1	K_2
12.61 GPa	7	0.79	1.6	0.07	0.61	0.04	1	85 GPa	–171 GPa
ρ	P_{crush}	U_{crush}	P_{lock}	U_{lock}	EF_{min}	F_c	F_s	T	K_3
2240 kg/m^3	16 MPa	0.001	800 MPa	0.1	0.01	37.1 MPa	–1	3.0 MPa	208 GPa

Among them: ρ – density, G – geotechnical shear modulus, S_{max} – maximum dimensionless strength, A – dimensionless viscosity constant, B – dimensionless pressure strengthening coefficient, C – strain rate coefficient, N – dimensionless pressure hardening index, D_1, D_2, EF_{min} – material damage constants, K_1, K_2, K_3 – material parameters, P_{crush}, U_{crush} – pressure and volume strain at crushing point, P_{lock}, U_{lock} –material compaction point pressure and volume strain, T – pressure constant, F_c – static yield strength of rock and soil, F_s – failure type.

6. ESTABLISHMENT OF SIMULATION MODELS

6.1. DIVISION OF FINITE ELEMENT MESH

The meshing of three-dimensional modeling can make the force and calculation of the model more accurate and improve the accuracy of the experiment. The meshing must be reasonable and the appropriate accuracy should be selected according to the actual situation. Too large grids can lead to negative volume, but too small grids can lead to too long analysis time. In this paper, the accuracy of drum, rock and pick is set as different values. The drum and rock take 0.02 mm grid size, and the pick part takes 0.005 mm accuracy. The drum part is divided by triangular grid shape, and the rock part uses square block to simulate the actual rock situation. The specific model is shown in Fig. 5.

In this paper, because the sequence of the picks is the same, so this paper intercepts one of the pick helix for simulation analysis. On this basis, the mesh model is obtained by meshing different alloy head angle, tooth spacing and impact angle.

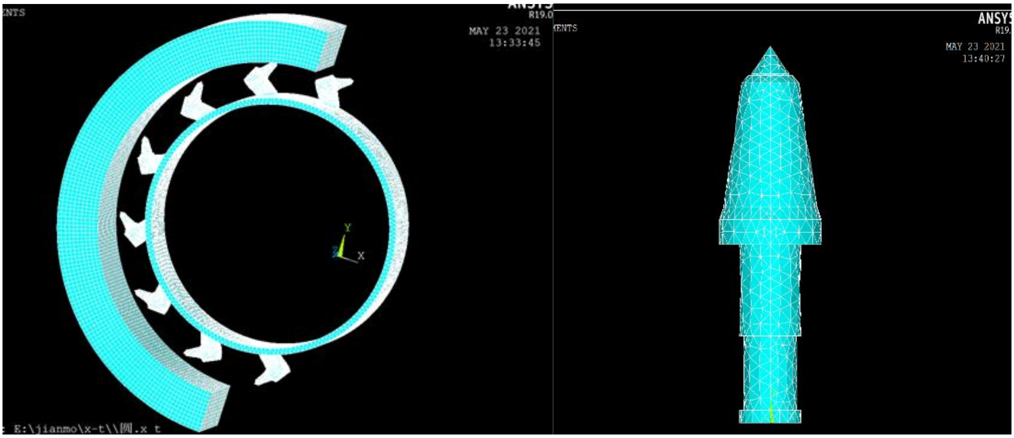


Fig. 5. Meshing of partial cutting drum and rock in LS-DYNA

6.2. CONTACT SETTINGS

The process from the contact between the pick and the rock to the rock fracture is a dynamic contact process. Therefore, the process of rock destruction by hobs is similar. Cutter and rock is a surface-to-surface contact problem between rigid and flexible bodies. Therefore, this paper simulates the use of erosion surface contact (ESTS), which has the advantages of fast calculation speed, low sand leakage energy and stability. Its keyword is CONTACT_ERODING_TO_SURACE.

6.3. BOUNDARY CONDITIONS AND CONSTRAINT SETTINGS

This design research is cutting drum cutting coal rock simulation, using part of the rock instead of underground rock conditions. Therefore, in order to avoid the influence of boundary reflection on the simulation results, this paper needs to restrict the rock part and add normal and tangential stress to offset the influence of boundary. In this paper, the non-reflective conditions are added to the other surfaces except the contact surface and the opposite surface of the broken rock, so as to achieve as close as possible to the real environment.

6.4. SOLUTION AND SOLUTION CONTROL

In the post-processing stage of LS-DYNA software simulation, this paper uses LS-PREPOST software to assist. LS-DYNA mainly defines the simulation parameters, and finally obtains the load and stress nephogram.

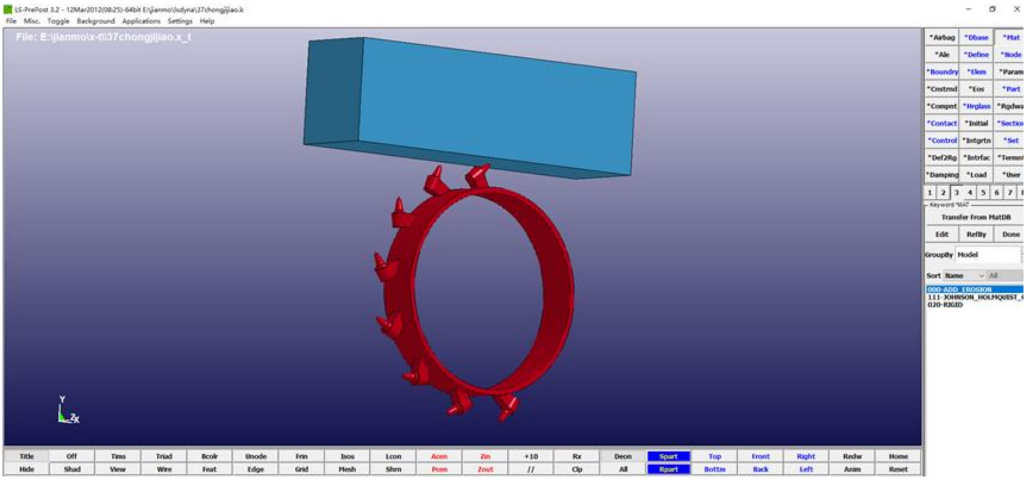


Fig. 6. LS-PREPOST post-processing interface

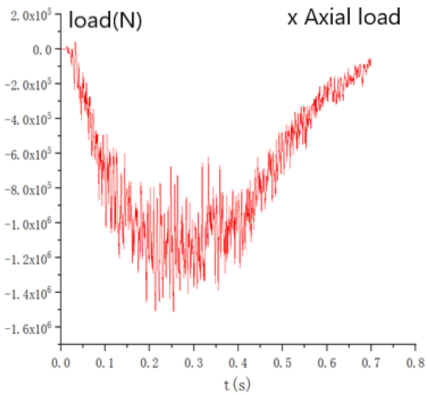
7. EFFECTS OF PARAMETERS ON CUTTING PERFORMANCE

7.1. EFFECT OF INTERCEPT LINE SPACING ON CUTTING PERFORMANCE

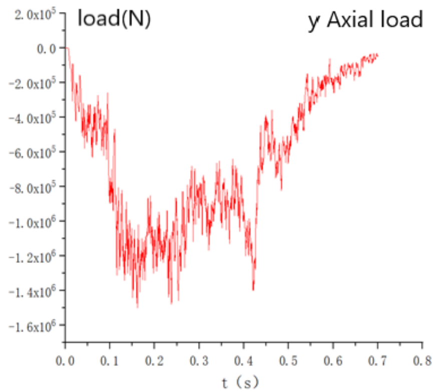
In this paper, 250 mm, 275 mm, 300 mm, 325 mm tooth spacing roller model simulation analysis, can get the three-dimensional cutting force of each model and the total cutting load changes with time line diagram, in this paper, 250 mm tooth spacing as an example, the simulation results are shown in Fig. 7.

According to Table 3, the relationship between the intercept distance and the load and torque in this paper can be obtained, and Fig. 7 can be drawn.

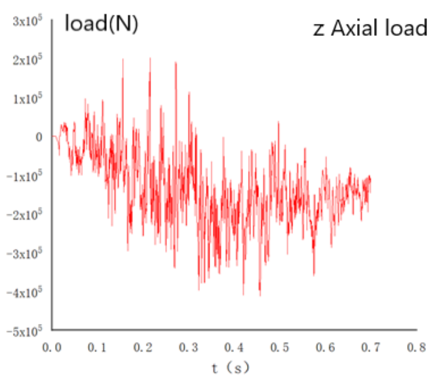
Figure 8 shows that when the tooth spacing is 250~275 mm and 300~325 mm between the upward trend, the change range is 6 kN, about 6%. Keep relatively stable load between 275 ~ 300 mm. From the load fluctuation point of view, basically in 250~275 mm time showed a downward trend, the change range is about 2 kN, about 4%, its parts are more stable. Overall, with the increase of tooth spacing, the force of the pick increases, the cutting ability of the drum decreases, and the cutting stability increases.



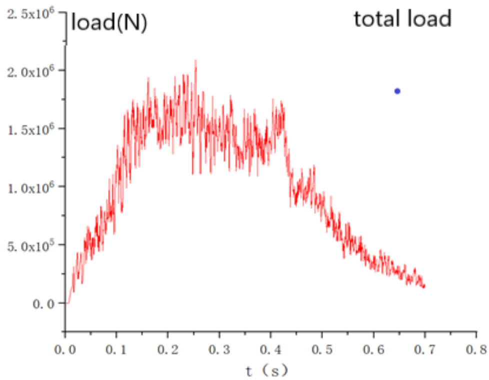
(a) *x* axial load



(b) *y* axial load



(c) *z* axial load



(d) total load

Fig. 7. Schematic diagram of load in each direction

Table 3. Load means and torque results of gear spacing rollers in each group

Interceptor spacing [mm]	Mean cutting resistance [kN]	Mean traction resistance [kN]	Mean total load [kN]	Standard deviation of cutting resistance	Mean cutting torque [kN*m]	Standard deviation of torque
250	76.65	65.75	104.6	36.59	45.99	21.95
275	83.65	72.95	115.6	37.15	50.19	22.29
300	83.64	73.46	115.6	36.85	50.18	22.11
325	84.95	83.15	121.6	35.25	50.97	21.15

It can be seen from Figure 9 that the change trend of cutting torque is very similar to that of load, and both keep an upward trend. Torque increased rapidly in 250~275 mm, the degree of change is 6 kN, about 12%, followed by a slow rise. Therefore, with the increase of tooth spacing, the torque and load of the pick in this paper are gradually increased. Therefore, in a certain range, this paper cannot set the spacing of the pick too large. At the same time, the smaller the spacing of the pick will increase the overall cost of the roadheader.

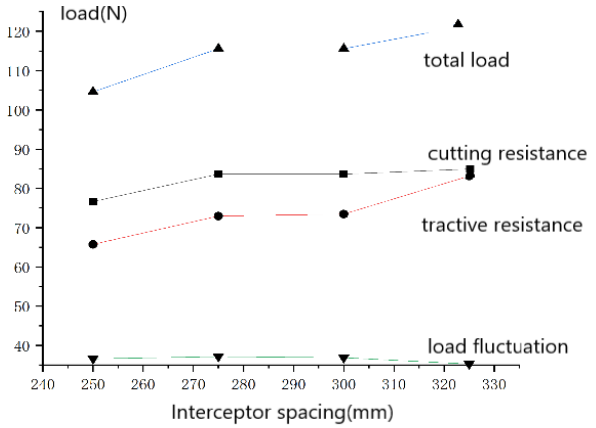


Fig. 8. Relationship between tooth spacing and cutting drum load

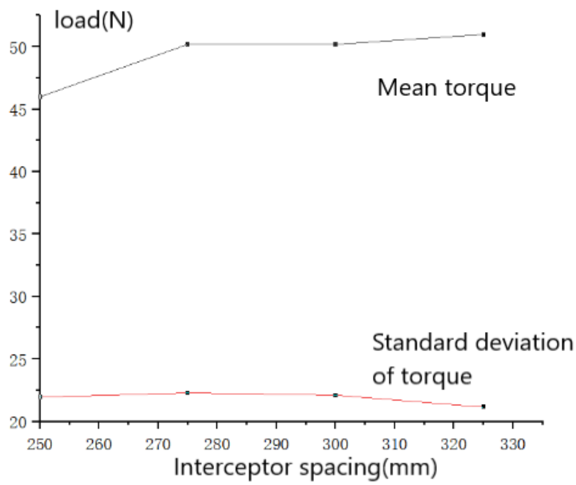


Fig. 9. Relationship between tooth spacing and torsional distance of cutting drum

According to Table 4, the relationship between tooth spacing and specific energy consumption of cutting drum can be obtained, as shown in Fig. 10.

Table 4. Specific energy consumption results of cutting drum tooth spacing in each group

Interceptor spacing [mm]	Mean torque [N*m]	Revolution speed [r/min]	Time [s]	Coal rock density [kg/m^3]	Dropped coal block [kg]	Cutting energy consumption [kWh/m^3]
250	45991	30	0.5	1594	6.25	5.11
275	50190	30	0.5	1594	6.14	5.43
300	50180	30	0.5	1594	5.79	6.74
325	50972	30	0.5	1594	5.46	6.89

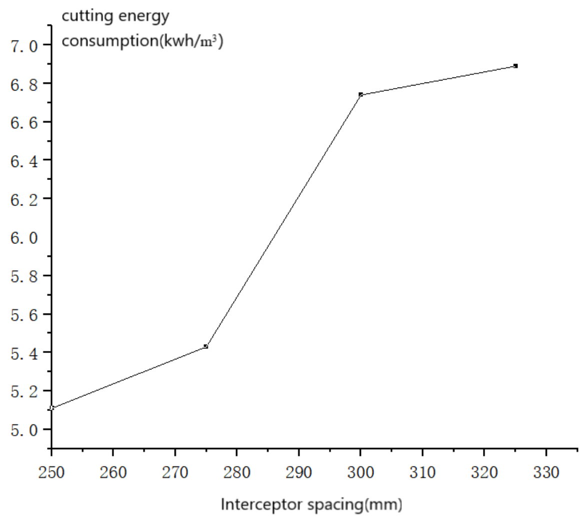


Fig. 10. Specific energy consumption of cutting drums with line spacing in each group

It can be seen from Figure 10 that the specific energy consumption of cutting increases with the increase of the intercept distance. When the intercept distance is between 275 mm and 300 mm, the specific energy consumption of cutting increases rapidly, and it grows slowly. The variation range of specific energy consumption is 1.8 kWh/m^3, about 26%. Therefore, it can be concluded that the larger the intercept distance is, the greater the energy required for cutting unit volume is, especially between 275 mm and 300 mm. So in the choice of tooth spacing as far as possible to ensure that the force of the pick is small, design a relatively small and reasonable tooth spacing.

7.2. EFFECT OF IMPACT ANGLE ON CUTTING PERFORMANCE

By changing the impact angle of the pick and simulating it, the external load of the following four groups of data can be obtained, as shown in Table 5.

Table 5. Impact angle load and torque results of each group

Angle of attack [°]	Mean cutting resistance [kN]	Mean traction resistance [kN]	Mean total load, [kN]	Standard deviation of cutting resistance	Mean cutting torque [kN*m]	Standard deviation of torque
30	85.15	73.85	116.4	38.63	51.09	23.18
37	83.64	73.46	115.6	36.85	50.18	22.11
45	82.25	71.85	113.1	39.87	49.84	23.40
52	81.47	70.43	112.3	39.82	48.88	23.89

under different impact angles can be drawn, as follows. According to Table 5, the relationship diagram of the load and torque of the pick

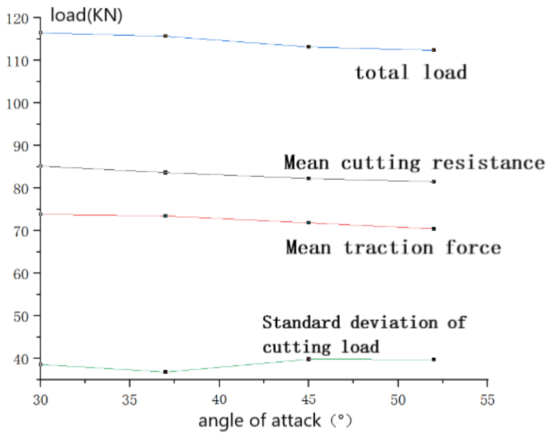


Fig. 11. Variation curve of impact angle and load of pick

It can be seen from Figure 11 that the load of the pick decreases slowly with the increase of the impact angle, and the decrease is small. Every 7° decreases about 1 kN, a total decrease of 4 kN, about 4%. The load of the pick at 52° is the smallest, which is 112 kN. Therefore, it can be concluded that when the impact angle of the pick increases, the load of the pick will decrease and the life of the pick will prolong, but the load fluctuation of the pick will also be larger, and the stability of the cutting will be reduced. It can be seen from the figure that the load fluctuation is the smallest when the impact angle is 37°, which indicates that there is a critical point of the minimum load fluctuation when the impact angle is between 30° and 45°.

In Figure 12, the torque suffered by the pick basically maintained a decreasing trend with the increase of the impact angle, and the fluctuation range was about 2 kN, about 4%. The fluctuation of cutting torque is very similar to that of cutting load. When the impact angle is near 37°, a minimum value can be obtained, and the working process of the drum in this area is the most stable.

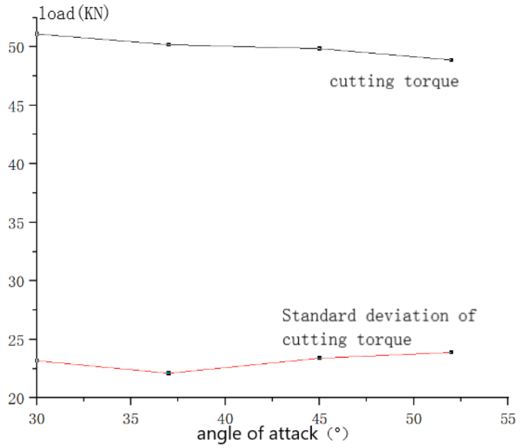


Fig. 12. The curve of the impact angle and the torque of the drum

Table 6. Cutting specific energy consumption results of impact angles

Impact angle of picks, [°]	Mean torque [N*m]	Revolution speed [r/min]	Time [s]	Coal rock density [kg/m^3]	Dropped coal block [kg]	Cutting energy consumption [kWh/m^3]
30	51090	120	0.5	1594	4.56	31.17
37	50180	120	0.5	1594	4.22	33.08
45	49840	120	0.5	1594	3.74	37.07
52	48880	120	0.5	1594	3.55	38.30

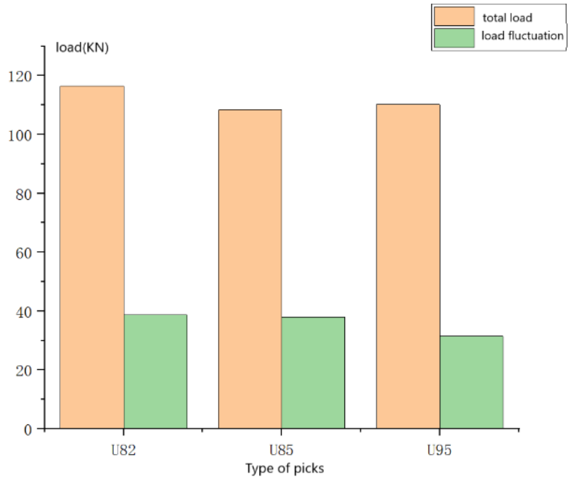


Fig. 13. Curves of impact angle and specific energy consumption

It can be seen from Figure 13 that when the impact angle increases, the specific energy consumption of cutting also increases. When the impact angle is between 37° and 45°, the growth is particularly obvious, and it slowly increases after 45°. The change of specific energy consumption of cutting is about 7 kWh/m^3, with about 18% fluctuation. It can be seen that the impact angle of the pick has obvious influence on energy consumption, so a low impact angle should be maintained as far as possible when selecting the impact angle of the pick.

7.3. EFFECT OF ANGLE OF ALLOY HEAD ON CUTTING PERFORMANCE

By changing the angle of the alloy head of the cutting head, the simulation model of the drum is reestablished and simulated, and the external loads such as cutting resistance can be obtained as shown in Table 7.

Table 7. Cutting load and torque of alloy head angle cutting teeth in each group

Angle of alloy head [°]	Mean cutting resistance [kN]	Mean traction resistance [kN]	Mean total load [kN]	Standard deviation of cutting resistance	Mean cutting torque [kN*m]	Standard deviation of torque
70	79.95	70.05	109.06	38.05	47.97	22.83
80	83.64	73.46	115.64	36.85	50.18	22.11
90	83.75	71.65	115.06	37.95	50.25	22.77
100	82.95	72.25	135.05	37.45	49.20	22.47

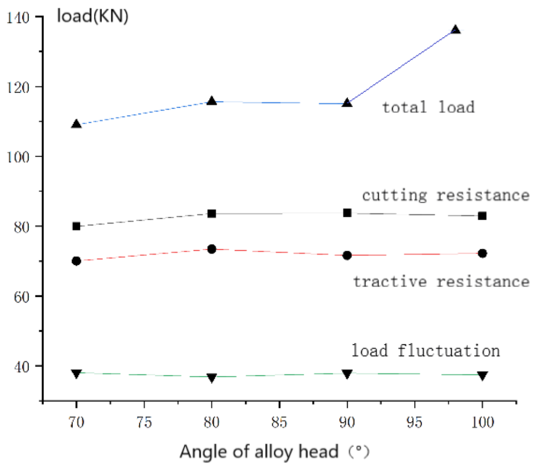


Fig. 14. Curves of angle of alloy head with load and torque

It can be seen from Fig. 14 that the influence of the angle of the alloy head on the pick load and torque is very small. Only when the pick angle is greater than 90°, there will be a significant change. Therefore, the load of the angle of the cutting head is not considered in this paper.

Table 8. Specific energy consumption results of each group of alloy head angle

Impact angle of picks [°]	Mean torque [N*m]	Revolution speed [r/min]	Time [s]	Coal rock density [kg/m^3]	Dropped coal block [kg]	Cutting energy consumption [kWh/m^3]
70	47970	120	0.5	1594	5.67	23.53
80	50180	120	0.5	1594	5.79	24.54
90	50250	120	0.5	1594	6.77	20.65
100	49200	120	0.5	1594	6.53	20.96

Figure 15 shows that the energy consumption of the pick-up ratio is about 24 kWh/m^3 at 70°~80°. At 80°~90° suddenly sharp decrease; a minimum value will be obtained at 90°, and the variation of specific energy consumption is 4 kWh/m^3, about 20%, which is relatively large. When the angle of the alloy head is 90°, the economic benefit of the pick is the highest, and the size of the alloy head will not affect the torque and load fluctuations. Therefore, this paper can take the 90° pick as the design reference of this paper.

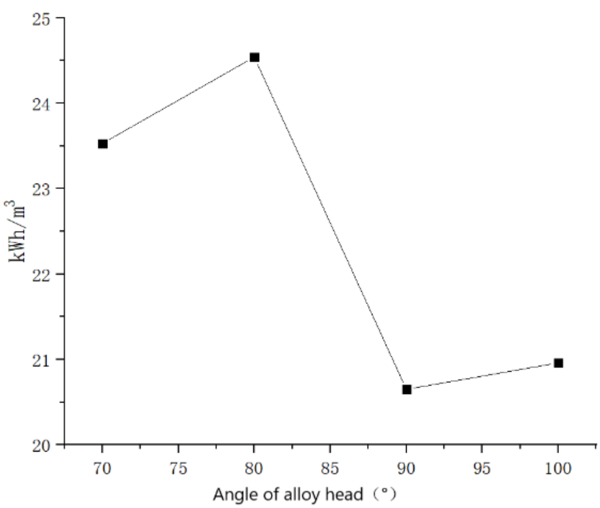


Fig. 15. Energy consumption curve of alloy head angle and cutting ratio

8. CONCLUSION

The angle of pick alloy head, pick impact angle and pick spacing are simulated, and the influence on cutting performance is analyzed by comparing their load, load fluctuation, torque and specific energy consumption. For the angle of the alloy head, within a certain range, the larger the angle is, the smaller the cutting energy consumption is. The cutting energy consumption of the 90° alloy head is the smallest, and the change of the angle of the alloy head has little effect on the load. For the impact angle of the pick, the load of 30° and the specific energy consumption per unit time are the smallest, and the torque and specific energy consumption increase linearly with the increase of the angle. For the tooth spacing, the greater the tooth spacing, the greater the load fluctuation, the greater the torque, and the greater the cutting specific energy consumption.

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