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INFLUENCE OF CUTTING ANGLE ON MECHANICAL PROPERTIES OF ROCK CUTTING BY CONICAL PICK BASED ON FINITE ELEMENT ANALYSIS

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Abstract: In view of the current situation that it is difficult to obtain the actual cutting force received by the conical pick of Continuous-Miner and to deal with the characteristics of the cutting force. By using contact dynamics, rock mechanics, and finite element methods, based on the display dynamics analysis program ANSYS/LS-DYNA and the Holmquist–Johnson–Cook model, the contact mechanical characteristics between conical pick and rock are analyzed. The resultant force was obtained by obtaining the force curve of the conical pick under *X*, *Y* and *Z* directions, analysis of cutting gear cutting speed of 2.5 m/s, cutting depth of 5, 10, 15, 20 and 25 mm, cutting angle of 30°, 35°, 40°, 45°, 50° parameters of the size of cutting force and cutting ratio energy consumption, thus, the best cutting angle of the conical pick is obtained. The conclusions are as follows: when the cutting depth and cutting speed are constant, and the cutting angle is 45°, the mean cutting force received by the conical pick is the least, the specific energy consumption is the least, and the cutting efficiency is the highest. The best cutting angle of the conical pick should be 45°; When the cutting angle and cutting speed are constant, the energy needed by the cutter to cut the rock increases with the increase of cutting depth. The research results provide a theoretical basis for improving cutting efficiency and cutting life, and for choosing cutting angle and cutting thickness.

Keywords**:** *conical pick, energy consumption ratio, cutting angle, computer simulation*

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1. INTRODUCTION

The position of Continuous-Miner in the process of coal mining is irreplaceable (Lin et al. 2020), good cutting performance is the basis of efficient mining in coal mines. Conical pick is the key part of Continuous-Miner (Qiao et al. 2021), and appropriate cutting angle can reduce the load fluctuation, improve cutting performance, reduce energy consumption and ensure the stability of Continuous-Miner. Proper cutting angle has great effect on improving coal mining efficiency. Optimizing cutting angle is the most effective way to improve the mining efficiency of Continuous-Miner.

Continuous-Miner in the mining work, mainly rely on conical pick will shock the coal off the coal (Ge 2020). The conical pick is subjected to a large impact load in the work, so the conical pick is the easiest to wear and damage parts. Therefore, the reasonable selection of cutting angle has positive significance for reducing the wear of Continuous-Miner body, reducing the consumption of conical pick of Continuous-Miner, improving the mechanical operation rate and increasing the comprehensive economic benefits of coal mining production (Wan et al., 2021). The analysis of the cutting angle is closely related to the load received by the conical pick in the process of rock breaking. The best cutting angle can be obtained by studying the load received by the conical pick.

Many scholars at home and abroad have carried out research on the cutting angle of conical pick, and the research is divided into two categories. The first is to build the cutting test bed, and obtain the external load on the conical pick through the sensor (Gospodarczyk et al. 2013). This method needs to invest a lot of money, from the research needs to spend time and economy is not adapted to the modern mining machinery design of high efficiency, reliability, low cost, low carbon economy requirements (Guo et al. 2021). The second is to use numerical simulation theory and computer technology as a new means and method of research, through three-dimensional software to build the conical pick and rock model, into ANSYS/LS-DYNA for calculation (Zhao et al. 2012). It can allow designers to accurately express the load characteristics of the conical pick in the process of rock breaking (Dolipski et al. 2017). It has the characteristics of low cost and high reliability, and has a huge application prospect. Taking the simulation results as the basis for the design of Continuous-Miner can improve the performance of conical pick (Chen 2021).

In this paper, the concept of specific energy consumption will be introduced. First, the situation of the minimum force on the conical pick is analyzed to obtain the cutting angle under the minimum comprehensive force on the conical pick. Then, the cutting angle is analyzed together with the specific energy consumption to explore whether there is the minimum specific energy consumption when the conical pick is subjected to the minimum cutting force. Only when the cutting force and specific energy consumption are small, can it be called the best cutting angle.

2. MODEL ESTABLISHMENT AND PARAMETER SETTING STEPS

2.1. SELECTION OF CONSTITUTIVE MODEL FOR ROCK MATERIALS

The Holmquist-Johnson-Cook model is adopted in this paper (Holmquist et al. 1993). This model is a material damage model proposed by T.J. Holmquist et al. The constitutive model is mainly used to solve the large deformation problems of rocks and other materials. It mainly focuses on the evolution of compression damage of materials, and considers the pressure dependence of compression strength, strain rate effect and damage softening effect. Its equivalent yield strength is a function of pressure, strain rate and damage, while pressure is a function of volume strain, and damage accumulation is a function of plastic volume strain, equivalent plastic strain and pressure. The model is mainly composed of three equations, namely yield surface equation, compression state equation and damage evolution equation.

The yield surface equation (Wu et al. 2010) is calculated as follows:

$$\sigma^* = [A(1-D) + BP^{*N}](1 + C\ln\varepsilon^*), \tag{1}$$

where, σ^* and P^* are the dimensionless equivalent stress and hydrostatic pressure obtained by dividing the actual equivalent stress and hydrostatic pressure, respectively, by the static compressive strength f_c' of the material; ε^* is the dimensionless strain rate obtained by dividing the real strain rate by the reference strain rate ε_0; D is the degree of injury; A, B, N and C are the strength parameters of the material.

The damage evolution equation (Su et al. 2020) is calculated as follows:

$$D = \sum \frac{\Delta\varepsilon_P + \Delta\mu_P}{\varepsilon_P^f + \mu_P^f}, \tag{2}$$

where, $\Delta\varepsilon_P$ and $\Delta\mu_P$ are equivalent plastic strains and plastic volumetric strains in a calculation cycle, respectively; ε_P^f and μ_P^f are the equivalent plastic strain and plastic volumetric strain of crushing under normal pressure, respectively.

The element failure criterion in the Holmquist–Johnson–Cook model is based on the custom strain failure criterion (Li et al. 2009). When the trial stress of a certain element in the rock exceeds its strength, plastic deformation will occur. When the plastic strain accumulates to the defined failure strain, LS-DYNA can delete this element by using erosion algorithm.

2.2. THE ESTABLISHMENT OF FINITE ELEMENT MODEL

Establish the model and set the parameters. The size of the rock model is 200 mm × 100 mm × 50 mm. Use SolidWorks software to build a three-dimensional model of conical pick and rock, save the assembly as $X{\cdot}T$ file and export it (Wang et al. 2021). Figures 1 and 2 show the diagram of conical pick model and diagram of conical pick and rock model, respectively.

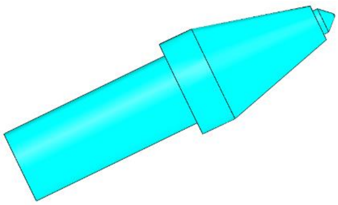

Fig. 1. Diagram of conical pick model

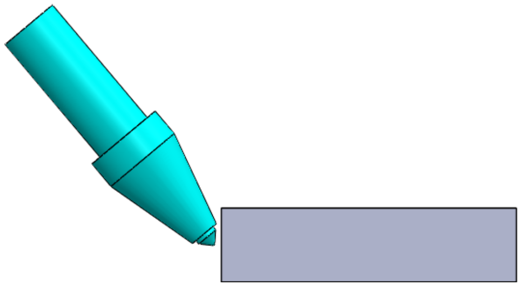

Fig. 2. Diagram of conical pick and rock model

Import the assembly model into ANSYS Multiphysics/LS-DYNA option in ANSYS software to set the unit type and divide the mesh (ANSYS/LS-DYNA Chinese Technology Support Center. Beijing Institute of Technology, 1999). In the Preprocessor_ Element Tpye option, set the model unit type to SOLID 164 entity unit. Set groups 1 and 2 in the Preprocessor_Material Props_Material Models option. Group the conical pick and rock models in the Preprocessor_Meshing_Mesging Attributes option. The conical pick is divided into group 1 and the rock model into group 2. The mesh is partitioned in the Preprocessor_Meshing_MeshTool option with the conical pick and rock mesh sizes of 0.005 and the conical pick and rock mesh shapes of triangles and rectangles. Figures 3 and 4 show the diagram of rock cutting by conical pick and diagram of meshing model, respectively.

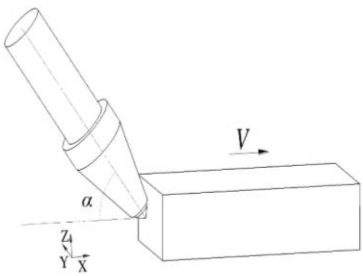

Fig. 3. Diagram of rock cutting by conical pick

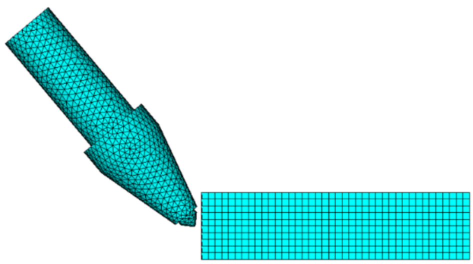

Fig. 4. Diagram of meshing model

In the Select Area option, select the four faces except the bottom and top. Next, set the four faces selected in the Select_Comp/Assembly_Creat Component option as Non-reflecting Boundary, the purpose of which is to simulate the infinite amplification of the boundary around the rock. Small rocks are used to simulate the infinite rock (Qian

2021). Activate the set Nonreflecting Boundary in the Solution_Constraints_Apply_Non-Refl Bndry option. In the Solution_Constraints option, select the base of the rock model and hold the base of the rock in place to limit the movement of the rock. In the Preprocessor_LS-DYNA Options_Contact_Define Contact option, set the type of Contact between the conical pick and the rock as Surface to Surf_Eroding and the Contact Component as 1. Set the operation time to 0.1s in the Solution_Time Controls_Solution Time option. The file is saved as K file and imported into LS_PREPOST simulation software to define material attributes and conical pick movement. This experiment mainly studies the force of the conical pick. The conical pick is set as a rigid body without considering the loss of the conical pick (Liu 2009).

2.3. CONICAL PICK AND ROCK MATERIAL PROPERTY DEFINITION

The material properties are defined. The density of the rock is set as 2670 kg/m^3, the density of the conical pick is set as 7800 kg/m^3, the Poisson's ratio of the rock and the conical pick is set as 0.3, the shear modulus of the rock is set as 1080 MPa, the compressive strength of the rock is set as 123 MPa, and the tensile strength of the rock is set as 5.16 MPa.

Table 1. Material parameter

Parts	Density [kg/m^3]	Poisson ratio	Shear modulus [MPa]	Compressive strength [MPa]	Tensile strength [MPa]
Rock	2670	0.3	1080	123	5.16
Conical pick	7800	0.3	–	–	–

2.4. SET THE CONICAL PICK MOTION CONSTRAINT

In the Mat_Rigid option, the motion constraint of the conical pick is set to restrict the movement of the conical pick in Y and Z directions and the rotation in X, Y and Z directions. The failure basis of unit was set in the MAT_ADD_EROSION. During the process of rock breaking by conical pick, the rock at the bottom and side is compressed and nonlinear deformation occurs. With the continuous cutting of the conical pick, cracks appear and expand inside the rock. When the rock reaches the damage condition, the element fails and is automatically deleted, forming a rock breaking track. Figure 5 shows the diagram of rock fracture trajectory model.

The moment of mass inertia of the model is set in the PART_INERIIA option, and the required data is obtained from the quality properties in SolidWorks. In the DEFINE_CURVE option, set the path of conical pick movement. Save the file as K file, and then import the set model into LS_DYNA software for simulation operation. Finally, the data are obtained for data analysis.

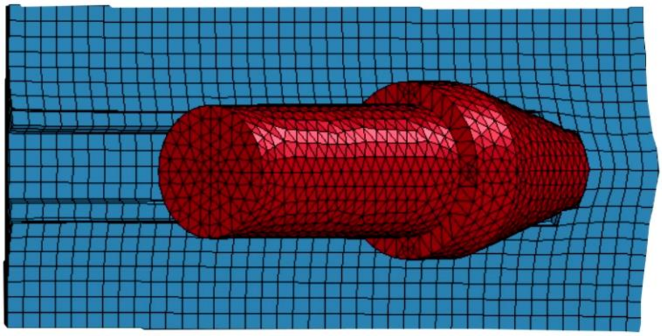

Fig. 5. Rock fracture trajectory

3. DATA ANALYSIS

3.1. CUTTING FORCE CALCULATION

The first step is to process the obtained data and calculate the cutting force according to the formula.

The calculation formula of the cutting force on the conical pick at a certain moment (Theoretical Mechanics Teaching and Research Group. Harbin Institute of Technology, 2016) is calculated as follows:

$$F_t = \sqrt[2]{F_{tx}^2 + F_{ty}^2 + F_{tz}^2}, \tag{3}$$

where, F_{tx} is the force exerted by the conical pick in the x direction at time t, in kN; F_{ty} is the force exerted by the conical pick in the y direction at time t, in kN; F_{tz} is the force exerted by the conical pick in the z direction at time t, in kN.

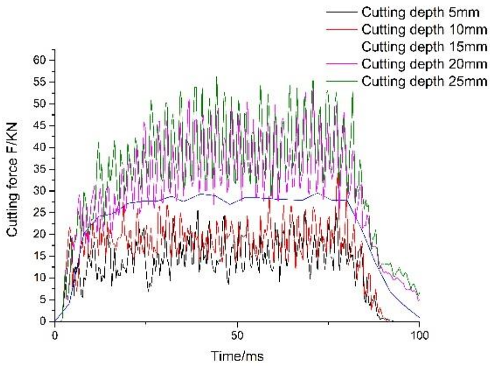

Fig. 6. Cutting force analysis diagram when cutting angle is 30°

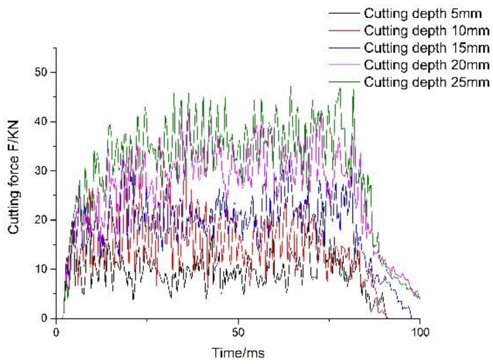

Fig. 7. Cutting force analysis diagram when cutting angle is 35°

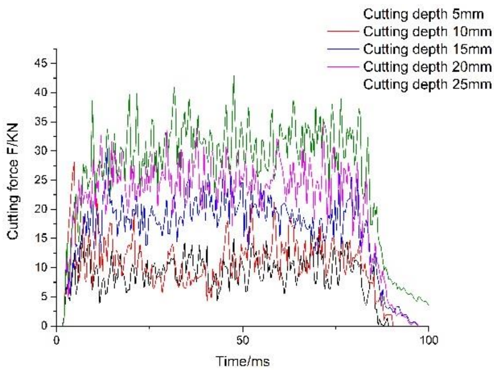

Fig. 8. Cutting force analysis diagram when cutting angle is 40°

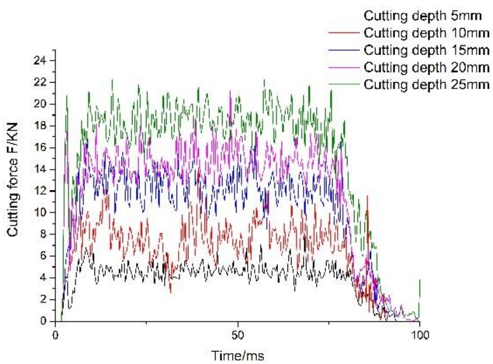

Fig. 9. Cutting force analysis diagram when cutting angle is 45°

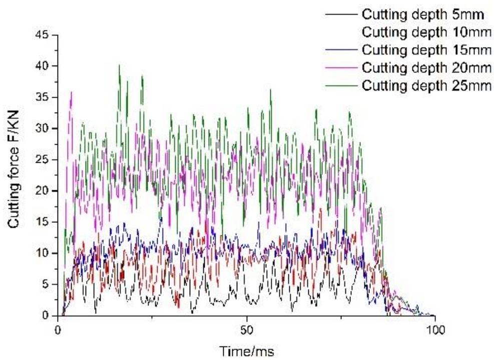

Fig. 10. Cutting force analysis diagram when cutting angle is 50°

The calculation formula of average cutting force (Zhu 1999) is calculated as follows:

$$\bar{F} = \frac{\int_{t_1}^{t_2} F_t dt}{t_2 - t_1}, \tag{4}$$

where, t_1 and t_2 are the forces at the beginning and end of the conical pick, respectively.

Figure 11 shows the average cutting force curve of the conical pick when the cutting angle of the conical pick is 30°, 35°, 40°, 45° and 50°, and the cutting depth is 5 mm, 10 mm, 15 mm, 20 mm and 25 mm, respectively. According to the five stress curves, when the cutting speed is constant, the minimum average value of the cutting force appears at the cutting angle of 45°. With the increase of cutting angle, the average cutting force decreases first and then increases. According to the figure, when the cutting angle is 45°, the data of average cutting force from bottom to top are 4.23 kN, 6.99 kN, 10.76 kN, 12 kN and 15.18 kN, respectively.

Figure 12 shows the maximum cutting force curve of the conical pick when the cutting angle of the conical pick is 30°, 35°, 40°, 45° and 50°, and the cutting depth is 5 mm, 10 mm, 15 mm, 20 mm and 25 mm, respectively. According to the five stress curves, except for the experimental group with the cutting depth of 15mm, the maximum cutting force of the other experimental groups showed a trend of decreasing first and then increasing with the increase of cutting angle. When the cutting angle was 45°, the maximum cutting force had a minimum value. According to the figure, when the cutting angle is 45°, the data of maximum cutting force from bottom to top are 7.98 kN, 14.26 kN, 16.84 kN, 21.35 kN and 22.3 kN, respectively.

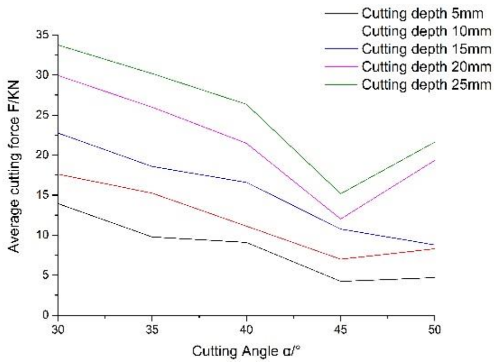

Fig. 11. Average cutting force analysis diagram

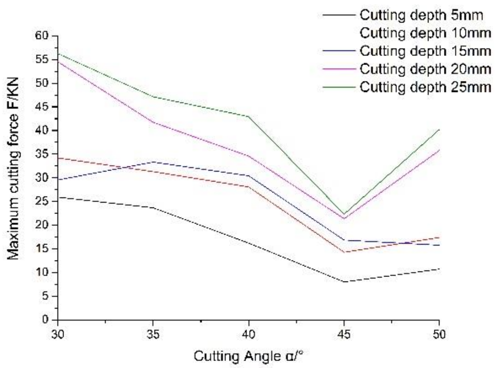

Fig. 12. Maximum cutting force analysis diagram

It can be seen from Figs. 11 and 12 that when the cutting speed is constant and the cutting depth increases, both the maximum and average cutting forces of the conical pick increase.

3.2. SPECIFIC ENERGY CONSUMPTION CALCULATION

In the second step, the cutting ratio energy consumption is calculated. The cutting ratio energy consumption is the energy consumed by the conical pick cutting unit volume of rock (Liu et al. 2017). Its theoretical mathematical expression is calculated as follows:

$$H_W = 2.78 \times 10^{-4} \frac{W}{V}, \tag{5}$$

where, H_W is the cutting specific energy consumption, in kJ/m^3; W is the work done by the conical pick in cutting rock, in kJ; V is the volume of cut rock, in m^3.

The formula of the work done by the conical pick in cutting rock (Kibble et al. 2004) is calculated as follows:

$$W = \int_{s_1}^{s_2} F_t ds = \int_{t_1}^{t_2} F_t v dt, \tag{6}$$

where, s_1 and s_2 are the distance at which the conical pick starts to contact the rock and the distance at which the conical pick stops to contact the rock respectively, in m; t_1 and t_2 are respectively the time when the conical pick starts to contact the rock and the time when the conical pick stops to contact the rock, in t; v is the cutting speed of conical pick, in m/s.

Figure 13 shows the cutting volume of the conical pick when the cutting angle of the conical pick is 30°, 35°, 40°, 45° and 50°, and the cutting depth is 5mm, 10mm, 15 mm, 20 mm and 25 mm, respectively. As can be seen from the figure, the cutting volume of all the experimental groups showed a trend of gradual increase with the increase of cutting depth.

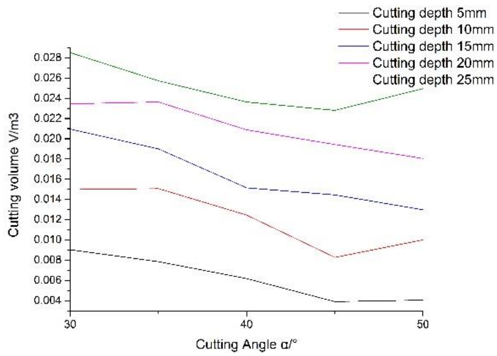

Fig. 13. Cutting volume analysis diagram

Figure 14 shows the total work done by the conical pick cutting rock when the cutting angles of the conical pick are 30°, 35°, 40°, 45° and 50°, respectively, and the cutting depth is 5 mm, 10 mm, 15 mm, 20 mm and 25 mm, respectively. It can be seen from the figure that, with the increase of cutting depth, the total work done by cutting rock shows a trend of gradual increase.

Figure 15 shows the specific energy consumption of rock cut by conical pick when cutting angles are 30°, 35°, 40°, 45° and 50°, respectively, and cutting depths are 5 mm, 10 mm, 15 mm, 20 mm and 25 mm, respectively. It can be seen from the figure that, when the cutting depth is constant, the minimum specific energy consumption occurs at the cutting angle of 45°, indicating that when the cutting angle is 45°, the cutting efficiency of the conical pick is the highest. According to the figure, when the cutting angle is 45°, the data of cutting ratio energy consumption from bottom to top are 42.1 kJ/m^3, 45.5 kJ/m^3, 47.6 kJ/m^3, 52.6 kJ/m^3 and 67.24 kJ/m^3, respectively.

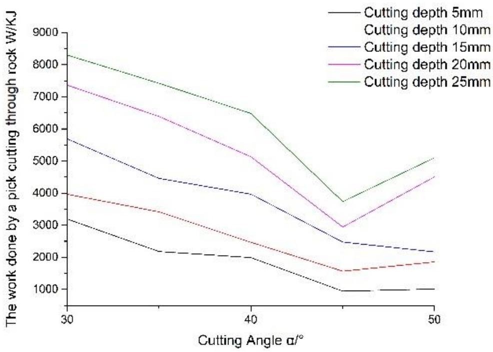

Fig. 14. Diagram of total work of rock cutting by conical pick

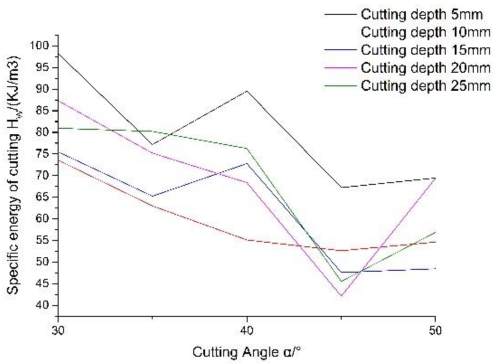

Fig. 15. Analysis diagram of cutting ratio energy consumption

According to the analysis in Figs. 14 and 15, when the cutting angle is constant, the energy consumed by the pick cutting rock also shows an increasing trend with the increase of the cutting depth. When the cutting depth is constant and the cutting angle is 45°, the minimum cutting specific energy consumption is obtained.

4. CONCLUSION

1) When cutting thickness and cutting speed are constant, with the increase of cutting angle, the mean value and maximum value of cutting force first decrease and then increase. In the above numerical simulation, when the cutting angle is 45°, the cutting force is the minimum and the cutting process is the most stable.

2) Cutting thickness has an effect on cutting force. With the increase of cutting thickness, cutting force increases and cutting energy consumption also increases, which aggravates the wear and energy consumption of conical pick. Comprehensive consideration, cutting thickness should not be too large.
3) When the cutting thickness and cutting speed are constant, the cutting specific energy consumption decreases first and then increases with the increase of cutting angle. In the above numerical simulation, when the cutting angle is 45°, the specific energy consumption is the minimum and the cutting efficiency is the highest.
4) To sum up, the best cutting angle of conical pick should be 45°.
5) Based on ANSYS/LS-DYNA 3D simulation processing method, it is of great significance to study the best cutting angle of conical pick, and then improve the mining and mining efficiency of Continuous-Miner.

ACKNOWLEDGEMENTS

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