Mining Science, vol. 30, 2023, 7–27

www.miningscience.pwr.edu.pl

Mining Science

(Previously Prace Naukowe
Instytutu Gornictwa Politechniki
Wroclawskiej, ISSN 0370-0798)

ISSN 2300-9586 (print)
ISSN 2353-5423 (online)

Received December 26, 2022; Reviewed; Accepted August 25, 2023

RESEARCH ON COMPREHENSIVE PERFORMANCE OF THE ARRANGEMENT OF PICKS ON THE CUTTING HEAD OF THE TRANSVERSE-AXIS DRIVING ANCHOR MACHINE

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Abstract: In this paper, the arrangement of picks on the cutting head of the transverse-axis driving anchor machine is analyzed and discussed, and two kinds of arrangement modes, namely sequential arrangement and punnett arrangement are studied. Based on the explicit dynamic analysis program ANSYS / LS-DYNA and the Holmquist-Johnson-Cook model, the contact mechanics characteristics between the pick and the rock are analyzed by using the theory and processing method of contact dynamics, rock mechanics and finite element. The maximum cutting force, average cutting force, cutting specific energy consumption and cutting force variance are obtained. By comparing the two groups of arrangement, it is concluded that the punnett arrangement is better than the sequential arrangement. Using MATLAB software to calculate the spectrum of cutting force, it is concluded that the main frequency is between 0 ~ 10Hz when the cutting head works.

Keywords: *pick, pick arrangement, specific energy consumption, cutting force analysis, cutting force spectrum*

1. INTRODUCTION

Transverse-axis driving anchor machine is a comprehensive mining equipment which integrates the functions of rapid excavation, support and transportation of coal roadway. It is mainly used in the excavation and mining of coal and rock roadway, and the cutting execution part is composed of cantilever and transverse-axis cutting heads (Ji-Heon. Kang et al., 2016). When working, the pick does spatial spiral motion, which can cut hard coal rock with large impedance.

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doi: 10.37190/msc233001

The cutting head of transverse-axis driving anchor machine directly acts on the cutting coal and rock, and there are many structural parameters, which are interrelated and mutually restricted. The pick is a part of cutting head, which directly acts on coal and rock. The relevant parameters of the pick have always been the research design (Qiao et al., 2021). In the actual working situation of transverse-axis driving anchor machine, the force difference of each pick is great, which not only causes serious vibration of the cutting head, but also causes great difference in the service life of each pick, which is not conducive to the repair and maintenance of the pick. The arrangement of picks will directly affect the force of picks, the specific energy consumption of cutting and the operation reliability and stability of transverse-axis driving anchor machine (Cheluszka et al., 2017). This paper compares the comprehensive performance of the cutting head of transverse-axis driving anchor machine, so that the difference of the external force of the cutting head is reduced, the load of the cutting head is reduced, so as to reduce the repair time of the cutting head, improve the service life of the cutting head and the cutting performance of the whole machine, and obtain the optimal arrangement.

Many scholars have also studied the arrangement of picks, such as Liu in 2009 established a coal and rock cutting experiment based on similarity theory, and studied the cutting performance and cutting system dynamic characteristics of cutting heads with different pick arrangements, it is concluded that the sequential arrangement broken hard lithology can be strong (Liu, 2009). In 2014, Zhao developed a load calculation program for different arrangement of picks with MATLAB software, and analyzed the reliability of different typical working conditions. The study found that under the same working conditions (Zhao et al., 2014), the use of Ponnet arrangement compared with the sequential arrangement reduces the specific energy consumption of cutting and increases the area of cutting coal. They made a deep research on the arrangement of picks and compared the advantages and disadvantages of sequential arrangement and punnett arrangement. In this paper, it is considered that the cutting depth should be introduced as a variable in the study of the pick arrangement, instead of only setting the cutting arrangement as a variable, because different cutting depth may lead to different results. Based on the research of the cutting angle of the pick, this paper continues to analyze and discuss the arrangement of the pick.

2. MODEL ESTABLISHMENT AND PARAMETER SETTING STEPS

2.1. SELECTION OF ROCK MATERIAL CONSTITUTIVE MODEL

This paper uses the Holmquist-Johnson-Cook model (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 volumetric 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:

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

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 (Yao. Li, 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. DETERMINE THE PARAMETERS OF THE HOLMQUIST-JOHNSON-COOK MODEL KEYWORD

In the LS-DYNA display dynamics analysis program, material parameters can be assigned to the finite element model by the Holmquist-Johnson-Cook model keyword file. The keywords of the Holmquist-Johnson-Cook model are shown in the figure. In the figure, MID is the material number assigned by the parameter, ρ is the material density (represented by RO in the figure), G is the material shear modulus, and ESPO is the material reference strain rate.

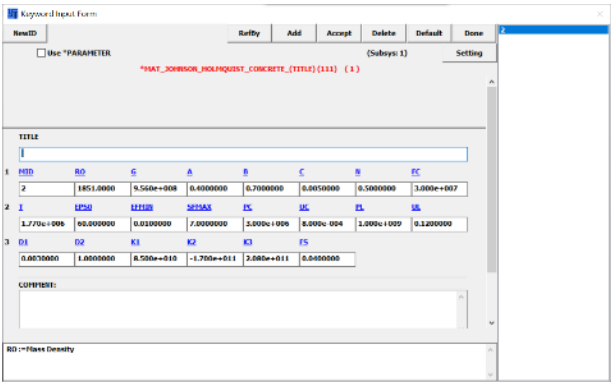

Fig. 1. The Holmquist-Johnson-Cook model parameter definition

2.3. THE ESTABLISHMENT OF FINITE ELEMENT MODEL

Establish the model and set the parameters (T. Stolarski et al., 2018). Use SolidWorks software to establish the three-dimensional model of the pick, pick seat posit, rotating support and rock model, and then merge the pick, pick seat posit, rotating support and rock model into assembly, save the assembly as x.t file and export. The cutting angle of the pick is set to 45° (Shuo. Qiao et al., 2021). The installation angle of the cutting angle is shown in the figure.

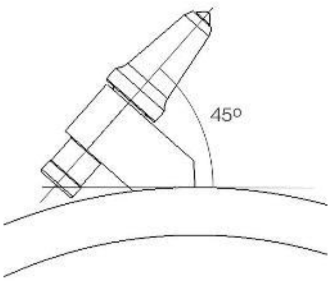

Fig. 2. Cutting angle of picks

In this paper, the internal stress of the pick is not analyzed. In order to facilitate the establishment of the simulation model and speed up the subsequent solving speed, the complex internal structure is omitted in the establishment of the 3D model, and the same shape of the 3D pick and pick seat posit is adopted. The simplified pick, pick seat posit, rotating support and rock model are shown in figure.

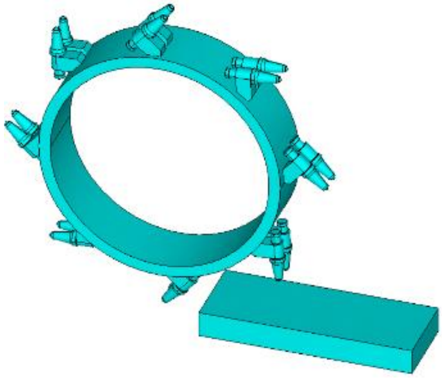

Fig. 3. 3D model schematic diagram

The research direction of this paper is to analyze and compare the comprehensive performance of two kinds of picks arrangement, sequential and punnett arrangement. The arrangement should be taken as a variable to ensure the same other parameters, such as the number of picks, rotation speed, speed and cutting depth. Sequential and punnett arrangement as shown in the figure.

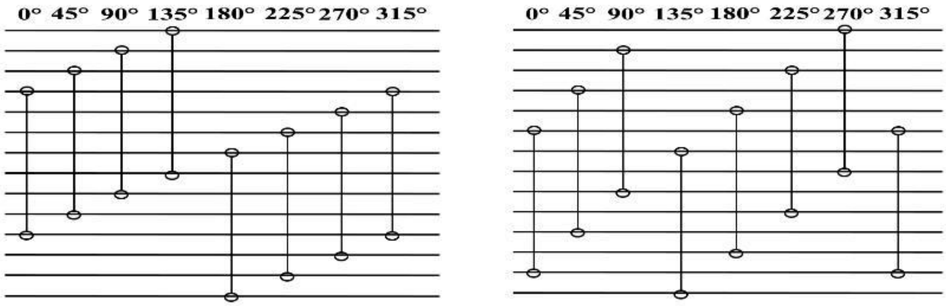

Fig. 4. Sequential and punnett arrangement diagram

2.4. PARAMETER SETTING OF FINITE ELEMENT MODEL

Import the assembly model into ANSYS Multiphysics/LS-DYNA option of ANSYS software to set the unit type and divide the grid (Y. Li et al., 2020). Set the model unit type to Solid 164 entity unit in the Preprocessor_Element Type option. Set 1~2 groups in the Preprocessor_Material Props_ Material Models option. Group picks and rock models under the Preprocessor_Meshing_Mesging Attributes option (T. Huang, 2015). Among them, the group 1 is the pick, pick seat posit, rotating support group, and the group 2 is the rock group.

```
The PART list has been created.

 LIST ALL SELECTED PARTS.

PARTS FOR ANSYS LS-DYNA
=======================
USED:  used in number of selected elements

      PART        MAT       TYPE       REAL       USED

         1          1          1          1     232840
         2          2          1          1     151200
```

Fig. 5. Model grouping diagram

Meshing is completed in the Preprocessor_Meshing_MeshTool option. The pick and rock mesh size is 0.005, the pick seat posit, rotating support mesh size is 0.05, and the pick, pick seat posit, rotating support and rock mesh shape is triangular. The meshed model is shown in the figure.

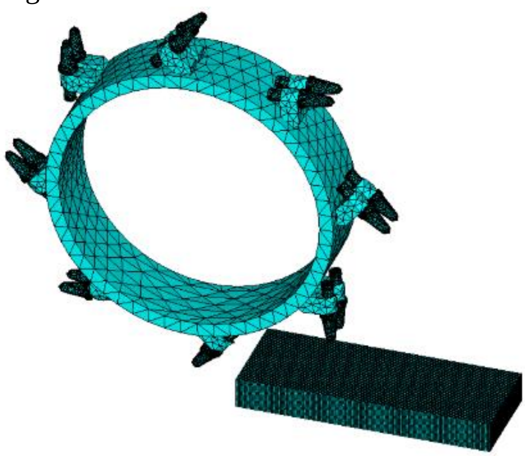

Fig. 6. Diagram of meshing model

Select five faces except the left in the Select area option. Then, in Select_Comp/Assembly_Creat Component, Select the five faces as nonreflecting boundary. The intention is to simulate an infinite enlargement of the rock boundaries. Use small rocks to simulate infinite rock. Activate the set nonrelecting boundary in the Solution_Constraints_Apply_Non-Refl Bndry option. Select the right side of the rock model in the Solution_Constraints option and fix the right side of the rock to limit the movement of the rock. Set the Contact type of pick and rock as Surface to Surf_Eroding in the Preprocessor_LS-DYNA Options_Contact_Define Contact, and set 16 picks, pick seat posit and 1 rotating support as Contact Surface. The rock model is set to TARGET SURFACE. Set the calculation time to 5s in the Solution_Time Controls_Solution Time option. The file was saved as K file and imported into LS_PREPOST simulation software to define material properties and pick motion. This experiment mainly studies the force of the pick, without considering the loss of the pick, set the pick as a rigid body (X. Zhang et al., 2021).

2.5. PICK AND ROCK MATERIAL PROPERTIES DEFINED

The material properties are defined. The density of the rock is set to 2670kg/m^3, the density of the conical pick is set to 7800kg/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 1080MPa, the compressive strength of the rock is set as 123MPa, and the tensile strength of the rock is set as 5.16MPa.

Table 1. Material parameter

Parts	Density (kg/m3)	Poisson ratio	Shear modulus (M/Pa)	Compressive strength (M/Pa)	Tensile strength (M/Pa)
Rock	2670	0.3	1080	123	5.16
Conical pick	7800	0.3	——	——	——

2.6. SET PICK MOTION CONSTRAINTS

In the Mat_RIGID option, set the motion constraint of the pick, restrict the pick's movement in Y and Z directions and limit the rotation in X and Y directions. The element failure basis was set in Mat_ADD_EROSION, and the rock at the bottom and side was squeezed during the rock fragmentation process, resulting in nonlinear deformation of the rock. As the pick continues to cut, cracks appear and expand inside the rock. When the rock reaches the damage condition, the unit fails and is automatically deleted, forming a rock breaking track. Rock cracks are shown here.

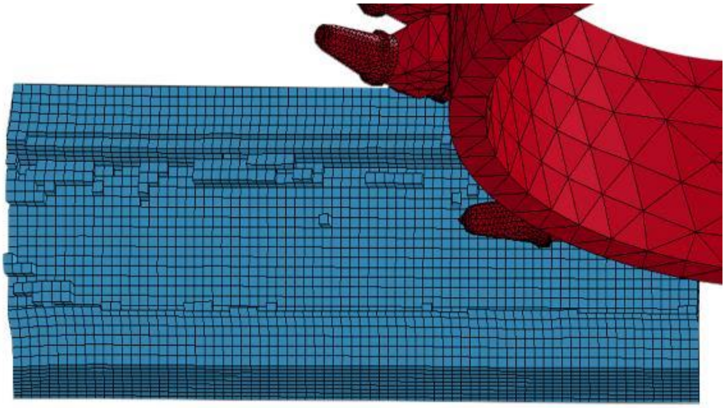

Fig. 7. Diagram of cutting trajectory

In the PART_INERIIA option, we need to set the mass moment of inertia for the model. The required data is obtained from the mass properties in SolidWorks. Set the path for the pick to move in Define_CURVE. Save the file as K file, and then import the set model into LS_DYNA software for simulation calculation. Finally, the data are obtained for data analysis.

3. DATA PROCESSING AND ANALYSIS

3.1. CUTTING FORCE CALCULATION

The first step is to process the obtained data and calculate the cutting force of the pick according to the formula (Theoretical Mechanics Teaching and Research Group, 2016).

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

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. 8. to Fig. 10. show the force curves calculated for sequential arrangement and punnett arrangement at the cutting depth of 10mm, 20mm, 30mm, 40mm and 50mm respectively.

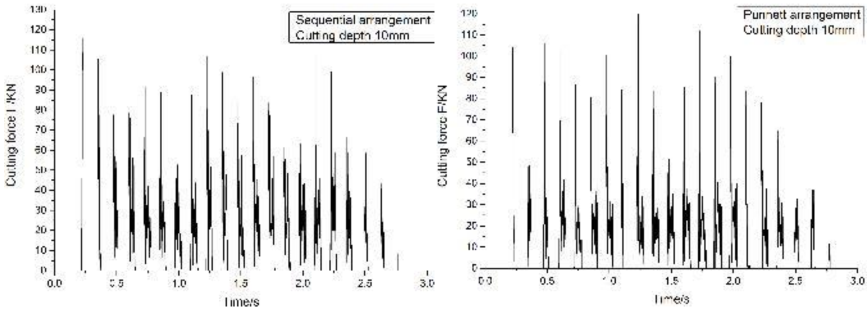

Fig. 8. Cutting force of sequential and punnett arrangement when cutting depth is 10mm

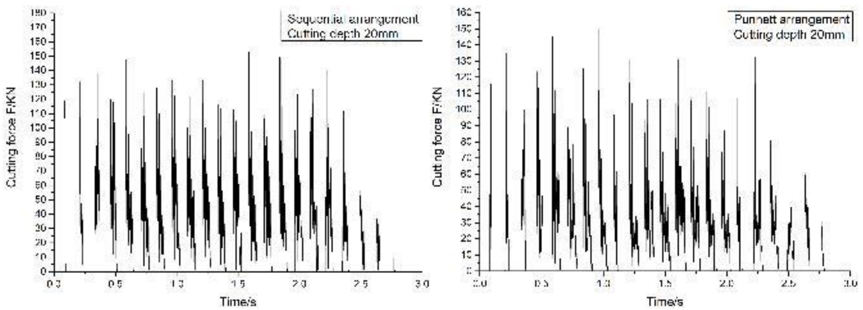

Fig. 9. Cutting force of sequential and punnett arrangement when cutting depth is 20mm

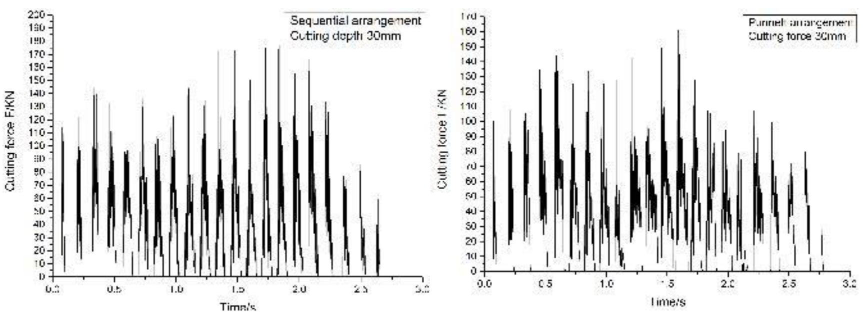

Fig. 10. Cutting force of sequential and punnett arrangement when cutting depth is 30mm

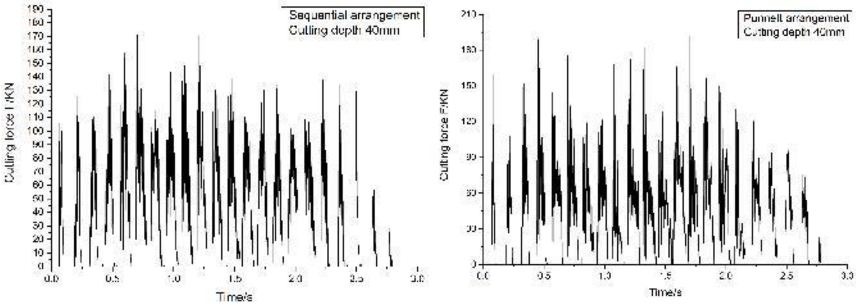

Fig. 11. Cutting force of sequential and punnett arrangement when cutting depth is 40mm

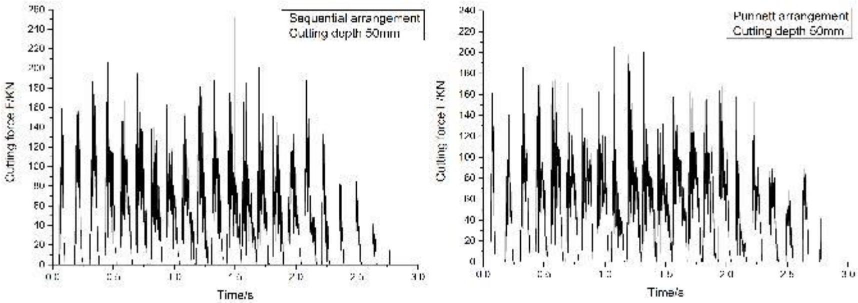

Fig. 12. Cutting force of sequential and punnett arrangement when cutting depth is 50mm

3.2. MAXIMUM CUTTING FORCE

Fig. 13. shows the maximum cutting force analysis diagram of sequential and punnett arrangement at 10mm, 20mm, 30mm, 40mm and 50mm respectively.

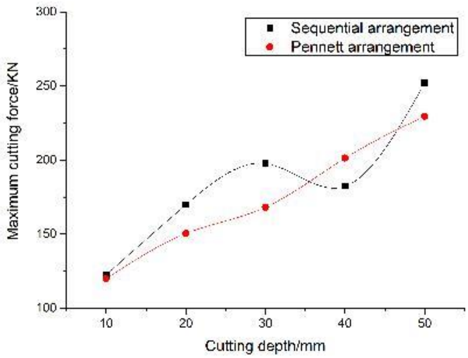

Fig. 13. Maximum cutting force analysis diagram

According to the analysis in the figure, when the cutting depth is 40mm, the maximum cutting force of sequential arrangement is smaller than that of punnett arrangement, and in other cases, the maximum cutting force of sequential arrangement is larger than that of punnett arrangement.

Table 2. Maximum cutting force date

	10mm	20mm	30mm	40mm	50mm
Sequential arrangement	122.53kN	169.76kN	197.63kN	182.20kN	251.98kN
Punnett arrangement	119.90kN	150.36kN	168.06kN	201.29kN	229.50kN

3.3. AVERAGE CUTTING FORCE CALCULATION

The calculation formula of average cutting force (J. Stewart, 2018) 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.

Fig. 14. shows the average cutting force analysis diagram of sequential and punnett arrangements at 10mm, 20mm, 30mm, 40mm and 50mm, respectively.

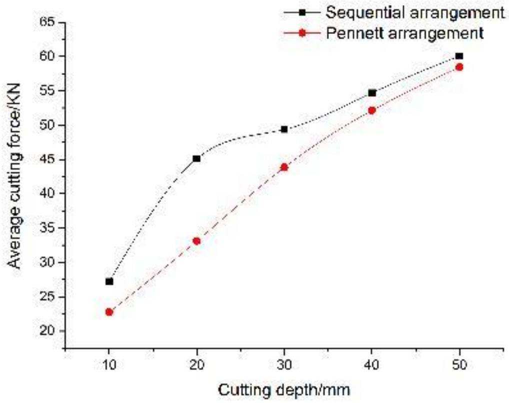

Fig. 14. Average cutting force analysis diagram

According to the analysis of the figure, under the same cutting depth, the sequential cutting force is larger than the punnett average cutting force.

Table 3. Average cutting force data

	10mm	20mm	30mm	40mm	50mm
Sequential arrangement	27.20kN	45.12kN	49.37kN	54.70kN	60.07kN
Punnett arrangement	22.74kN	33.12kN	43.86kN	52.14kN	58.46kN

3.4. SPECIFIC ENERGY CONSUMPTION CALCULATION

The second step is to calculate the cutting specific energy consumption (Chunsheng. Liu et al., 2019). The cutting specific energy consumption is the energy consumed by the pick to cut the rock per unit volume, and its theoretical mathematical expression is as follows:

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

Where, H_W is the cutting specific energy consumption, the unit is KJ/m^3;
W is the work done by the conical pick in cutting rock, the unit is KJ;
V is the volume of cut rock, unit is m^3.
The formula of the work done by the conical pick in cutting rock 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, and the unit is 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, the unit is t;
v is the cutting speed of conical pick, the unit is m/s.

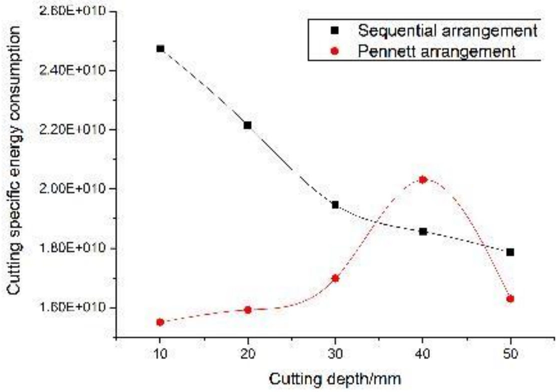

Fig. 15. Diagram of cutting specific energy consumption

Fig. 15. shows the cutting specific energy consumption when the sequential arrangement and punnett arrangement are respectively arranged, and the cutting depths are respectively 10mm, 20mm, 30mm, 40mm and 50mm. As can be seen from the figure, when the cutting depth is 40mm, the specific energy consumption of punnett arrangement is higher than that of sequential arrangement, and the specific energy consumption of sequential arrangement is higher than that of punnett arrangement under other conditions. The performance of punnett arrangement is better than that of sequential arrangement.

Table 4. Cutting specific energy consumption date

	10mm	20mm	30mm	40mm	50mm
Sequential arrangement	2.47E+10	2.22E+10	1.95E+10	1.86E+10	1.79E+10
Punnett arrangement	1.6E+10	1.6E+10	1.7E+10	2E+10	1.6E+10

3.5. CALCULATION OF CUTTING FORCE VARIANCE

Variance is the degree of deviation from the center, which measures how much a batch of data fluctuates (how much the batch of data deviates from the average) and is called the variance of the set of data. The greater the variance, the greater the fluctuation of data, the more unstable.

According to the obtained data, the variance of cutting force is calculated by the following formula (R. Figliola et al., 2011):

$$\sigma^2 = \frac{1}{N}\sum_{n=1}^{N}(F_t - \bar{F})^2 \tag{7}$$

Where, N is the number of sampling points;

σ^2 is the variance, the unit is kN^2.

Fig. 16. shows the diagram of variance of cutting force of sequential and punnett arrangement at 10mm, 20mm, 30mm, 40mm and 50mm, respectively.

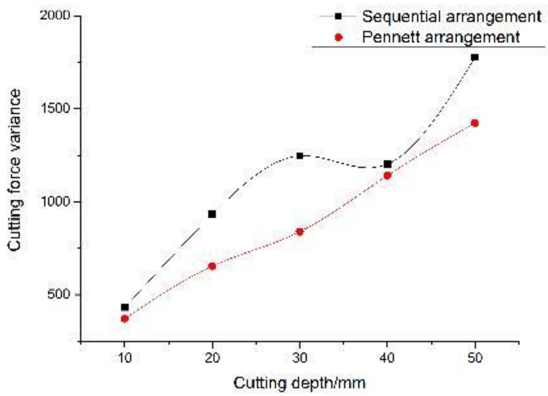

Fig. 16. Analysis of variance of cutting force

According to the analysis in the figure, under the same cutting depth, the variance of sequential arrangement is larger than that of punnett arrangement, indicating that the fluctuation of cutting force of punnett arrangement is more stable than that of sequential arrangement.

Table 5. Cutting force variance data

	10mm	20mm	30mm	40mm	50mm
Sequential arrangement	431.6021	932.0401	1246.502	1202.352	1775.355
Punnett arrangement	371.3646	653.9074	839.3378	1141.073	1423.396

3.6. FREQUENCY SPECTRUM ANALYSIS

The frequency spectrum of a signal is determined by its time domain properties, and Fourier analysis is the Fourier transform of a time domain signal, which is converted into a frequency domain signal for analysis.

According to the obtained cutting force data, it was imported into MATLAB for cutting force frequency spectrum analysis (C. Q. Wang, 2019), and the Fourier transform formula was as follows:

$$X(f) = \left|\int_{-\infty}^{\infty} F_t e^{-j2\pi f t} dt\right| \tag{8}$$

Where, $X(f)$ is amplitude, the unit is kN.

The MATLAB code for converting time domain signals into frequency domain signals is as follows:

```
>> t=0:0.0004:3;
>> n=length(film name);
>> fs=1/0.0004;
>> x=film name;
>> y1=fft(x);
>> y2=fftshift(y1);
>> f=(0:n-1)*fs/n-fs/2;
>> hold on;
>> plot(f,abs(y1),'r');
>> plot(f,abs(y2),'b');
>> axis([0,inf,0,inf]);
>> obj = get(gca,'children');
>> x=get(obj(2), 'xdata');
>> y=get(obj(2), 'ydata');
```

Fig. 17. to Fig. 21. show the frequency spectrum curves calculated by sequential and punnett arrangement at the cutting depth of 10mm, 20mm, 30mm, 40mm and 50mm respectively.

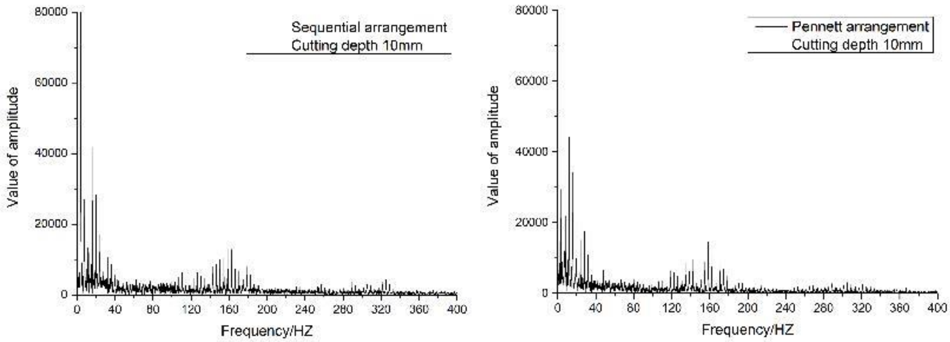

Fig. 17. Frequency spectrum of sequential and pennett arrangement when cutting depth is 10mm

As can be seen from the figure, the main frequencies of sequential arrangement are mainly concentrated in 0~30Hz and 120~180Hz, while the main frequencies of punnett arrangement are mainly concentrated in 0~30Hz Hz and 120~180Hz.

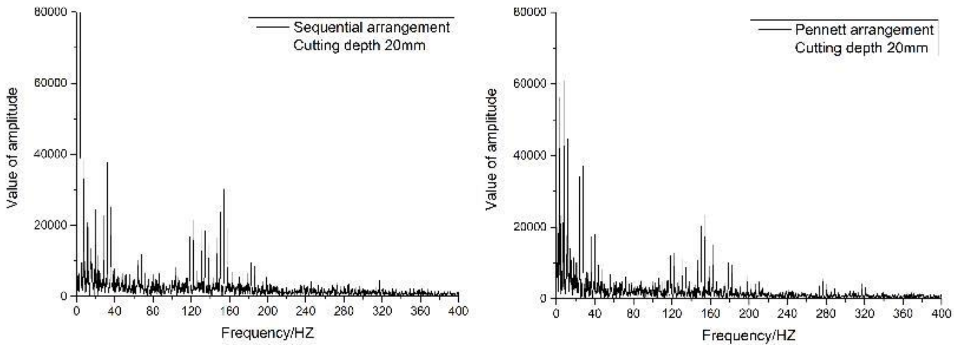

Fig. 18. Frequency spectrum of sequential and pennett arrangement when cutting depth is 20mm

As can be seen from the figure, the main frequencies of sequential arrangement are mainly concentrated in 0~40Hz and 120~160Hz, while the main frequencies of punnett arrangement are mainly concentrated in 0~40Hz Hz and 120~160Hz.

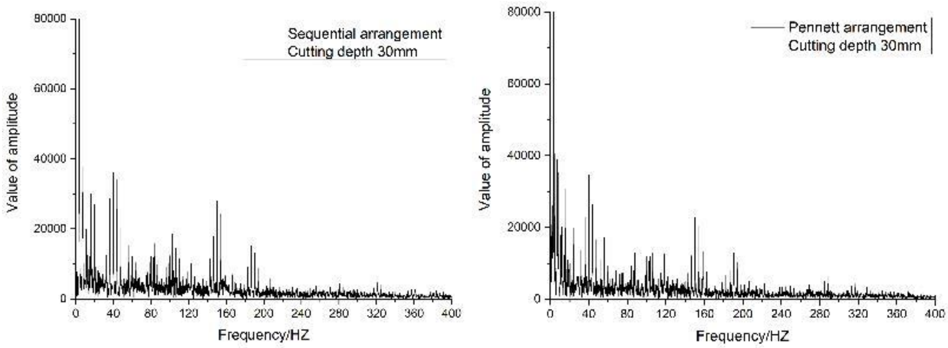

Fig. 19. Frequency spectrum of sequential and pennett arrangement when cutting depth is 30mm

As can be seen from the figure, the main frequencies of sequential arrangement are mainly concentrated in 0~20Hz, 35~45Hz, 140~160Hz and 180~200Hz, while the main frequencies of punnett arrangement are mainly concentrated in 0~20Hz, 30~60Hz, 140~160Hz and 180~200Hz.

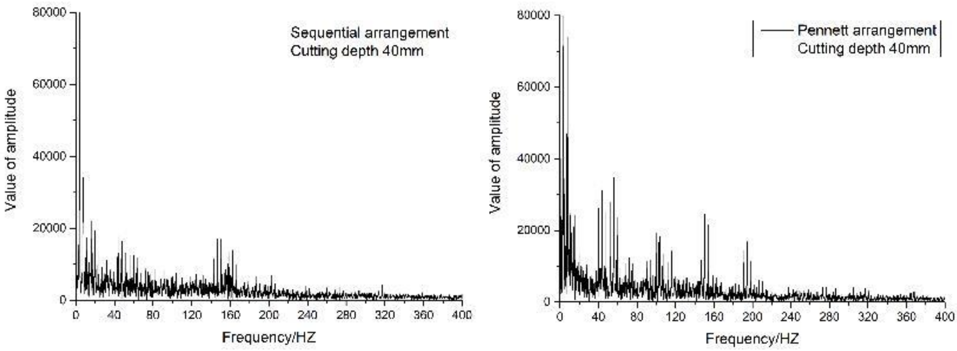

Fig. 20. Frequency spectrum of sequential and pennett arrangement when cutting depth is 40mm

As can be seen from the figure, the main frequencies of sequential arrangement are mainly concentrated in 0~30Hz, 40~60Hz and 140~160Hz, while the main frequencies of punnett arrangement are mainly concentrated in 0~20Hz, 40~60Hz, 90~110Hz, 140~160Hz and 190~210Hz.

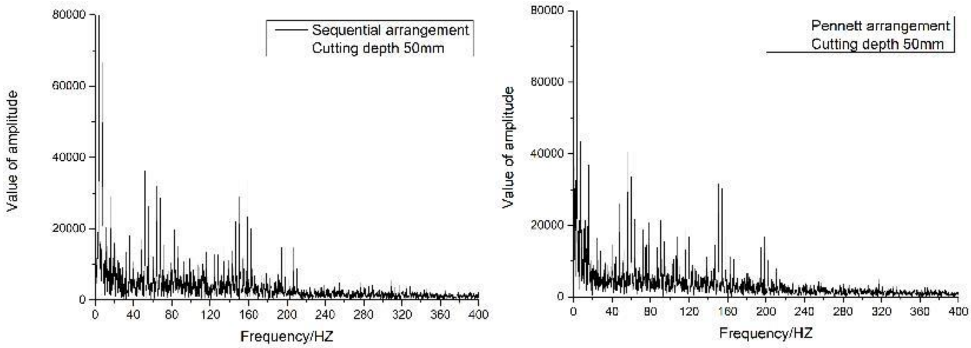

Fig. 21. Frequency spectrum of sequential and pennett arrangement when cutting depth is 50mm

As can be seen from the figure, the main frequencies of sequential arrangement are mainly concentrated in 0~10Hz, 50~70Hz, 140~160Hz and 190~210Hz, while the main frequencies of punnett arrangement are mainly concentrated in 0~20Hz, 50~120Hz, 140~165Hz and 195~210Hz.

According to the analysis from Fig. 17. to Fig. 21., when the value is taken in the main frequencies, the energy will be too large, leading to violent vibration of the cutting head, while the energy corresponding to other frequencies is relatively small and stable. However, we could not get the law of the main frequency concentration from the single spectrum, so the sequential and punnett arrangement frequency spectrum were superimposed respectively to obtain Fig. 22.

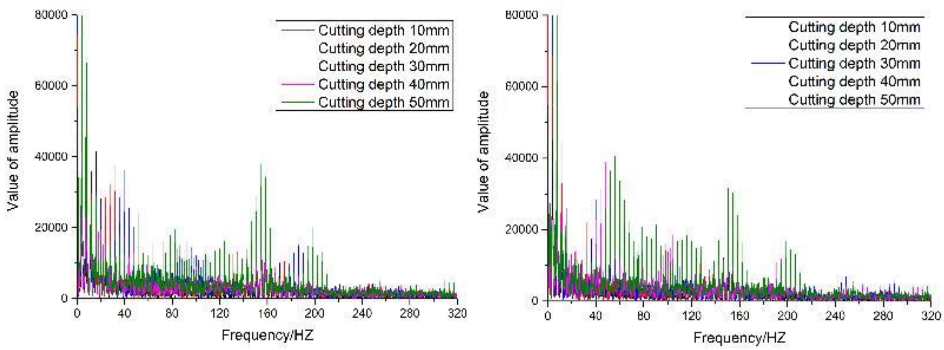

Fig. 22. Permutation superposition frequency spectrum about sequential and punnett arrangement

It can be seen from Fig. 22. that when the arrangement of pick is determined, the main frequency tends to move towards higher frequency with the increase of cutting depth. When the frequency is between 0 and 10Hz, and the smaller the value is, the higher the energy value corresponding to the ordinate is, the natural frequency of the cutting head should be far away from the main frequency range in the design

4. CONCUSION

1. When the cutting depth and cutting speed are constant, the Ponnet arrangement has better comprehensive performance than the sequential arrangement. When designing the cutting head of the horizontal axis drive bolt machine, the Ponnet arrangement should be given priority.

2. When the cutting speed and pick arrangement are fixed, and the frequency is between 0 ~ 10Hz, and the smaller the value, the higher the energy value corresponding to the ordinate, the natural frequency of the cutting head should be far away from the main frequency range in the design.

ACKNOWLEDGEMENTS

This study was financially supported by the National Natural Science Foundation of China (52105243), the Hunan Provincial Natural Science Foundation of China (2020JJ4646), the Research Foundation of Education Bureau of Hunan Province, China (19C0168).

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