Cutting Test and Finite Element Analysis of Plow Pick

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ABSTRACT The pick is the working part of the coal plow, the cutting performance of the pick is very important for the efficient production of the coal mine. In order to analyze the dynamic characteristics of the plow pick during the cutting process, a cutting test platform was built. The force of the plow pick and the vibration of the plow head were obtained through the cutting test, and the relationship between the vibration of the plow head and the cutting speed and cutting depth was analyzed. In order to study the influence of different alloy head shapes on the performance of plow pick, two kinds of pick were designed: a pick with chip bit and a pick with conical bit. The finite element method was used to establish the cutting model, and the numerical simulation was carried out. The research results show that the caving effect of pick with chip bit is better than that of pick with conical bit, but the cutting resistance of the pick with chip bit is greater than pick with conical bit. When the cutting angle is 60°, the force of the pick is the smallest and the force of the pick increases with the increase of the installation angle. The maximum error of the force of the pick obtained by the two methods is 8.41%. The cutting test verified the results of the numerical simulation. According to the research results, two types of pick were adopted in the coal plow, which were installed in different positions. Through the analysis of the actual working state of the plow, it is found that the damage form of the pick was consistent with the result of numerical simulation.

INDEX TERMS Plow pick, cutting performance, cutting test, finite element analysis.

I. INTRODUCTION

The recoverable reserves of thin coal seam account for about 20% of the total recoverable reserves of coal in China [1]–[3]. Coal plow is one of the important coal mining equipment in the production of thin seam coal mine. It has the advantages of simple and reliable structure, low price, easy maintenance, shallow cutting depth, large lump coal rate and easy realization of coal mining automation [4], [5]. Therefore, coal plow is suitable for mining extremely thin and thin coal seams with high coal dust and gas content, and the coal plow has a wider application prospect in China. A coal plow is composed of plow head, plow chain, guide chain and power transmission device.

Plow head is the executive mechanism of coal plow, which is composed of plow body and tool carrier equipped with various picks [6], [7]. The cutting performance of plow pick is very important for the efficient production of coal mine. Zhang established the symbiotic time-varying dynamic equation of longitudinal vibration and collision vibration of plow head, and analyzed the dynamic characteristics of plow system under different cutting conditions [8]. Hao analyzed the influence of pick width and distance between plow picks on cutting resistance by simulation [9]. Kang analyzed the force of the plow head and the influencing factors of the stability of the plow head [10], [11]. Yasar carried out rock cutting test with chisel pick, and obtained the variation law of average cutting force, maximum cutting force and specific energy of chisel pick with spacing depth ratio [12]. At present, the majority of coal mining machinery adopts...
conical pick, which is mostly used in shearer and roadheader, and many researches on cutting coal and rock have been carried out. Dewangan analyzed the wear of the pick by SEM, and found that the main wear mechanisms leading to failure [13]. Liu analyzed the cutting performance of the pick under different influence factors through experiments and numerical simulations [14], [15]. Qiao simulated the cutting process of single cone pick and double cone pick, and compared with the cutting test on the coal cutting machine [16]. Liu analyzed the influence of traction speed, drum angular speed and pick installation angle on the pick cutting force through discrete element numerical simulations [17]. Wan studied the cutting performance of shearer drum under different conditions [18]. The above research on pick is helpful to understand the mechanism of coal rock fragmentation and improve the performance of coal mining machinery.

Coal plow adopts flat pick, which is different from the pick type of shearer and roadheader, and the plow pick is an important part when the plow cutting the coal wall [19], [20]. The research on the cutting performance of the flat pick is helpful to improve the performance of coal plow. The structural design of the plow pick directly affects the load characteristics and working reliability of the whole plow system [21]. Due to the complex and changeable geological conditions, the force of coal plow has strong nonlinearity, instantaneity and randomness, and the function relationship of its parameters is very complex, and the load calculation results by using coal breaking theory are quite different from the actual ones [22], [23]. In this paper, the cutting process of two kinds
plow pick was simulated based on the finite element method, the contact load spectrum between the plow pick and the coal wall, the time history curve of the parameters such as the stress of the plow pick are obtained, which provides more scientific load data for the reliability analysis of the coal plow. Based on the test platform of mechanical properties of coal plow, the force of the plow pick and the vibration of the plow head were tested, and the cutting test verified the results of the numerical simulation.

II. CUTTING TEST
The cutting test system was composed of BH38/2 × 630 coal plow, SGZ764/800 scraper conveyor, ZY4800/07/19D hydraulic support, SZZ1000/400 transfer machine and manually poured coal wall. The whole cutting test system was installed on the basis of steel plate welding. In order to save the cost of the cutting test, two complete hydraulic supports are installed in the system, and the other supports only retain the pushing hydraulic cylinder, which is used for pushing and sliding the middle groove of the scraper conveyor. The actual object and layout of the test system are shown in Figure 1. The simulated coal wall in the test was constructed by mixing coal blocks of different sizes with cement, water reducing agent, etc., and then pouring layer by layer to ensure that the properties of the simulated coal wall were consistent with the actual coal wall. The coal plow was equipped with wireless sensor and signal acquisition and transmission device, which can measure the three-dimensional force of pick and vibration acceleration value of plow head in real-time on-line.

The pick with conical bit was used in the cutting test, and two grooves of 25 mm × 15 mm × 4 mm were machined on the pick body of the plow pick, three groups of Bx120-1bb strain gauges were fixed in the grooves by the half bridge patch method, which were used to measure the force of plow pick in X, Y and Z directions. After the strain gauge was welded, it was wrapped with 703 silica gel and stainless steel plate. The vibration detection system of plow head was composed of piezoresistive acceleration sensor, plow head, data processing and display unit. In order to facilitate the layout of the data acquisition line, the sensor was installed at the left end of the central top pick holder. Due to the large number equipment and complex environment, the use of wired data transmission will affect the cutting test. The wired transmission line is easy to be damaged and affect the data acquisition. The real-time data acquisition was carried out through the wireless acquisition module, and the data was transmitted to the computer through the wireless network [24]. The schematic diagram of data communication is shown in Figure 2. In order to protect the sensor and data collector, the cover plate was used for packaging. Through the data acquisition system in the test platform, the force of plow pick in the cutting process can be obtained. The force of plow pick when cutting the coal wall with thickness of 40mm at the speed of 1.83 m/s was collected, and the force curve is shown in Figure 3. The study shows that the force was nonlinear in the process of cutting the coal wall.

The horizontal acceleration of plow head was obtained by vibration sensor, as shown in Figure 4. Due to the gap between the plow head and the sliding frame, the plow head has a large vibration. The vibration in the horizontal direction mainly affects the cutting depth of the plow pick, and the change of the cutting depth aggravates the fluctuation of the force on the plow pick.

Figure 5 shows the vibration variation law of plow head with different cutting depths and cutting speeds. The vibration of the plow head decreases with the increase of the cutting depth and the cutting speed, and the influence of the cutting depth on the vibration of the plow head is more obvious.

III. FINITE ELEMENT ANALYSIS
A. ESTABLISHMENT OF FINITE ELEMENT MODEL
According to the shape of alloy bit, the plow pick can be divided into two types. The structure of the two types of pick is shown in Figure 6. The plow pick was composed of two alloy bits and a pick body. The alloy bit and pick holder were defined as rigid materials, which can simplify the model, save calculation time and have little effect on the results. Use the keyword *CONSTRAINED_XTRA_NODES_SET can realize the connection between pick and pick holder. The 8-node solid164 element was used in the whole model, and
the default constant stress element formula was used. The coal wall adopts hexahedral mapping grid, and the mesh of contact area was fine; the pick was irregular shape, which was divided into tetrahedral free mesh, and the mesh density is controlled locally. The mesh of contact part, fillet and stress concentration area was fine; the pick holder was rigid material, and the number of elements was reduced as far as possible to shorten the solution time [25]. The finite element model including coal wall, plow pick and pick holder is shown in Figure 7. The thickness of the pick body of the two picks is 25mm, the installation angle of the planer is 0°, and the cutting angle is 40°.

Coal is a typical viscoelastic plastic material. The cutting process of coal by plow pick is a complex non-equilibrium and non-linear evolution process. There are not only elastic-plastic deformation and brittle fracture, but also creep, relaxation and other rheological behaviors. Therefore, it is very important to select a constitutive relation which can comprehensively reflect the coal response in the process of breaking. Considering the characteristics of coal crushing behavior, the key word *MAT_DRUCKE_PRAGER material model was used to simulate the plastic constitutive relation of coal, and the key word *MAT_ADD_EROSION is adopted to define material failure [26], [27].

The mechanical parameters of coal can be obtained by experiments, as shown in Figure 8. The rigid materials of alloy bit and pick holder can be obtained through the key-word **MAT_RIGID. The material of pick body was linear elastic material, which was defined by the keyword

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**FIGURE 5.** Vibration acceleration of plow head. (a) Vibration acceleration with different cutting depths. (b) Vibration acceleration with different cutting speeds.

**FIGURE 6.** Structure of the plow pick. (a) Pick with chip bit. (b) Pick with conical bit.

**FIGURE 7.** Finite element model. (a) Cutting model of pick with chip bit. (b) Cutting model of pick with conical bit.
**MAT_ELASTIC.** The material parameters involved in the finite element model are shown in Table 1.

Under the condition that the calculation results are not affected, in order to shorten the solution time, the key word *CONTROL_TIMESTEP* in LS-DYNA can be used to scale the model quality, and the keyword *BOUNDARY_NON_REFLECTING* can be used to apply non-reflection boundary conditions to the coal wall to simulate the actual coal mining face [28]. After the contact parameters in the file and the type and frequency of the output file were set, they were submitted to the solver for solution.

## B. NUMERICAL SIMULATION RESULTS

The cutting groove formed by two types of picks after cutting was obtained by simulation, as shown in Figure 9. Under the same working conditions, although the width of the two picks is the same, the width of the groove formed by pick with chip bit is obviously larger than that of pick with conical bit, and the caving angle of chip bit is also larger than that of conical bit. Therefore, the caving effect of pick with chip bit is better than that of pick with conical bit.

The stress distribution of the two picks and the stress of the maximum stress element are shown in Figure 10 and Figure 11. The stress concentration position of pick with chip bit occurs in the welding area between alloy bit and pick body. Element 8974 and 18488 are located at the corner of the welding between the pick body and the alloy bit, and the element 34508 is located at the fillet between the front edge and the upper side of the pick body. The stress fluctuation range of element 34508 rises suddenly in 0.14s to $1.562 \times 10^3$ Mpa. The larger stress units of pick with conical bit appear at the top of the pick body and these elements are in the outer area of pick body contacting with coal wall. Element 84693 and 80768 are located on the lower side of the pick body, and the stress of element 90788 presents stage fluctuation, which will lead to the aggravation of wear; The average stress of element 99041 on the front edge of pick body increases with time, and the maximum instantaneous stress is $2.515 \times 10^3$ MPa. The value has exceeded the yield stress of the pick body, which is related to the local temperature rise caused by the increase of internal energy with time, the main damage of conical bit is wear failure.

The force of pick when cutting coal wall is shown in Figure 12. It can be seen from Figure 12 that the cutting force in
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TABLE 1. Material parameters in the model.

| Material      | Density / kg m$^{-3}$ | Elastic modulus / MPa | Poisson ratio | Cohesive force / MPa | Friction angle / rad | Sturdy coefficient |
|---------------|-----------------------|------------------------|---------------|-----------------------|----------------------|-------------------|
| Coal          | 1.319e3               | 5.24e3                 | 0.31          | 3.11                  | 1.03                 | 2.38              |
| Alloy bit     | 1.435e4               | 5.4e5                  | 0.3           | -                     | -                    | -                 |
| Pick body     | 7.85e3                | 2.125e5                | 0.3           | -                     | -                    | -                 |

Z direction is the largest, the lateral force in X direction and normal force in Y direction are less than the average cutting force. The values of lateral force and normal force fluctuate above and below zero, which indicates that the direction of lateral force and normal force is uncertain. Comparing the force of two picks, it is found that the average force of pick with chip bit was greater than that of pick with conical bit, this is because the front edge of chip bit is larger than that of pick with conical bit, which results in more energy needed for coal and rock mass collapse and crushing.

The forces of two kinds of plow pick under different cutting depths and cutting speeds were obtained through simulation, as shown in Figure 13. The cutting force and normal force of plow pick increase significantly with the increase of cutting depth, but the increase of lateral force is not particularly obvious. When the cutting depth is 40mm, the cutting force and normal force of pick with chip bit are 2.57 times and 2.03 times of that of 10mm. The cutting force and normal force of pick with conical bit are 2.49 times and 2.0 times. When the cutting speed is 4m/s, the cutting forces of the pick with chip bit and the pick with conical bit are 1.82 times and 1.77 times that of 1m/s. The normal forces of the pick with chip bit and the pick with conical bit are 1.24 times and 1.22 times that of 1m/s.

Through numerical simulation, the forces of pick with conical bit with different cutting angles and installation angles were obtained, as shown in Fig. 14. With the increase of the cutting angle, the force of pick decreases first and then increases. The force of the pick is the smallest when the cutting angle is 60°. The force of the pick increases with the
TABLE 2. The force information of plow bit obtained by two methods.

| Force / kN         | Cutting speed m/ s⁻¹ | Cutting depth / mm |
|--------------------|-----------------------|--------------------|
|                    | 0.5  | 1.0  | 1.5  | 2.0  | 10   | 20   | 30   | 40   |
| Cutting test       |      |      |      |      |      |      |      |      |
| Cutting force       |      |      |      |      |      |      |      |      |
| Finite element analysis |    |      |      |      |      |      |      |      |
| Relative error / % |      |      |      |      |      |      |      |      |
| Cutting test       |      |      |      |      |      |      |      |      |
| Normal force       |      |      |      |      |      |      |      |      |
| Finite element analysis |    |      |      |      |      |      |      |      |
| Relative error / % |      |      |      |      |      |      |      |      |
| Lateral force      |      |      |      |      |      |      |      |      |
| Finite element analysis |    |      |      |      |      |      |      |      |
| Relative error / % |      |      |      |      |      |      |      |      |

increase of the installation angle, and the change of cutting force and normal force is obvious, but the increase of lateral force is larger.

The effective values of the forces were obtained, as shown in Table 2 and Figure 15. The force of the plow obtained from the cutting test and simulation is basically consistent. The
maximum error of the plow bit obtained from the numerical simulation and cutting test under different cutting conditions is 8.41%. By comparing the two analysis methods, it can be detected that the finite element analysis can reflect the actual cutting state of the plow pick.

There is a gap between the plow head and the sliding frame due to the manufacturing, assembly accuracy and the wear when the plow head and the sliding frame move relative to each other, as shown in Figure 16. The gap leads to the continuous contact and collision between the plow head and the sliding frame in the actual working process, causing vibration. The vibration of the plow head will cause the change of the cutting depth of the plow pick, resulting in the fluctuation of the force on the plow pick, which has an impact on the stability and reliability of the coal plow system.

The plow was used in Nanliang coal mine in Yulin, Shaanxi Province, China. According to the analysis results, the pick with chip bit was selected for the top and bottom pick, and the pick with conical bit was used for the middle pick, as shown in Figure 17. The top and bottom pick can produce larger cutting groove, so the compression and tension effect of coal wall can be used to reduce the stress of the middle pick. With the increase of cutting depth and cutting speed, the vibration of the plow head will become smaller. Considering the reliability of the plow bit and the productivity of the coal mine, the cutting depth was 30 mm and the cutting speed was 2 m/s.

The damage state of the pick after long-term mining is shown in Figure 18. It can be seen from the figure that the wear of the pick, especially the inlaid part of the alloy bit, was serious, which will cause the alloy bit to easily fall off. The actual working state of the pick was basically consistent with the results of numerical simulation.

IV. CONCLUSION

In order to analyze the influence of chip bit and conical bit on the cutting performance of picks, the finite element numerical simulation analysis of coal cutting process of two types pick
was carried out, the shape of slot cut by plow pick, load spectrum of pick and coal wall contact and curves of plow pick’s parameters such as stress and strain time history were obtained, which provides a new method for obtaining the load of the plow and analyzing the reliability of the plow pick. The research results show that the coal rock caving effect of pick with chip bit is better than that of pick with conical bit, but the cutting resistance of the former is greater than that of the latter. The damage of pick with conical bit is mainly caused by alloy bit falling off, and the damage of pick with chip bit is mainly caused by wear. Based on the test platform of mechanical properties of coal plow, taking the cutting depth and cutting speed as variables, the force of the plow pick and the vibration of the plow head are tested, and the results are compared with the simulation results, the maximum error of cutting force, normal force and lateral force obtained by two methods is 8.41%. The correctness of the finite element simulation is verified by the cutting test. Through the analysis of the vibration of the plow head under different conditions, the results show that due to the gap between the plow head and the sliding frame and the change in the force of the plow pick, the plow head will vibrate violently, and the vibration of the plow head will be to a certain extent. The cutting depth and cutting angle of the plow pick will change due to the vibration of the plow head, which increases the fluctuation of the plow pick force. The vibration of the plow head decreases with the increase of the cutting depth and the cutting speed. According to the research results, two types of pick were adopted in the coal plow, which were installed in different positions, the motion parameters of the plow were adjusted in the industrial test, and good results were achieved.

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