Research Article

Influence of Coal Cleats on Conical Pick Cutting Process Based on PFC

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With the rising mining mechanized level, the conical pick, as the primary cutting tool, is widely used in mining machines, for example, continuous miners, drum shearers, roadheaders, etc. cut various rocks and minerals directly. Since the 1980s, by means of theory, experiments, and simulations, research studies on cutting performance or characteristics of conical pick, such as cutting force, parameters, wear and energy consumption, etc., have attracted extensive attention in the academic and engineering fields.

The cutting force of the conical pick is related to the cutting parameters when the cutting material is determined and always has been the research focus. Based on vertical cutting, the cutting force of the conical pick model was deduced by Evans [1], in which the cutting force was considered to be related to the tensile stress of coal, the semitip angle of the conical pick, and the cutting depth. Based on linear cutting tests at different depths and rocks, the peak and mean cutting forces were calculated by Ranman [2] and Goktan and Gunes [3] using only the input energy per unit of cutting length and semempirical prediction equations, respectively. A rotary cutting force model of conical pick was proposed based on Evans’ theory, and the effects of conical pick geometric parameters, installation angle, and cutting speed in the shearer cutting coal process were calculated by Liu et al. [4]. Linear and rotary conical pick cutting models were established by Zhang et al. [5] and Liu et al. [6], respectively, with EDEM (extended discrete element method) based on homogeneous coal, and the influence of cutting depth on the cutting force was studied.

The wear of the conical pick is its main failure form, which determines its service life, and greatly impacts the cutting efficiency. From 1969 to 1988, the Bureau of Mines of...
U.S. carried out various cutting experiments on different specifications of cemented carbide and diamond conical picks and evaluated the service life, cutting force, wear rate, friction spark, and so on of the conical picks [7]. A series of full-scale conical pick cutting sedimentary rock tests with different wear degrees were conducted, and the impact of pick wear on cutting force and specific energy was analyzed by Dogruoz et al. [8]. To better understand the wear mechanism of conical pick, the linear cutting experiments of conical pick were carried out and a rock fragmentation model was established, and the main reasons for the wear of conical pick were discussed by Li et al. [9]. In view of the serious wear types of conical pick with mining equipment, it was found that the wear decreases and increases with the increase of pick cutting angle and inclination angle, respectively [10]. ES-FEM (edge-based smoothed finite element method) and PFC numerical models of conical pick were built by Fan et al. [11] and Zhang et al. [12], respectively, which offered the solutions to improve the wear resistance of pick. There are some conical pick cutting models with PFC based on different confining pressures of coal to explore the load distribution and wear of conical pick [13, 14]. Meanwhile, there are some studies on cutting energy consumption [15, 16] and cutting dust [17, 18] of conical pick.

In the above research, the cutting materials, such as coal, granite, sandstone, and so on, were often considered with certain hardness, viscosity, stiffness characteristics, and even homogeneous property. However, the cutting materials are always composed of mass, cleats (or joints), holes, coalbed methane [19], etc., maybe mixed with partings [20], under different gas pressure conditions [21] and have different failure modes. There are a few studies about how the structure and mechanical properties of rock affect the cutting process of conical pick. The conical pick cutting coal with different distribution of parting models was built in LS-DYNA; the thicker the rock parting is, the closer the distribution position of parting is to the middle and bottom of coal and the greater the cutting force of the pick is [22].

Because cleats are inherent structures of coal, the research on how cleats affect the cutting process of conical picks will reveal the relationship between energy consumption and cutting force of the pick and put forward some theoretical suggestions on the mining or tunnel construction technology. The objective of this work is to get the effect of cleats on the cutting process of conical pick based on the cutting coal process of shearer. The simulation models of conical pick cutting process are built with PFC, which can conveniently simulate the discontinuity, initiation, and expansion of cracks and chip formation of rock, based on analyzing the cutting process of conical pick, determining the cleat spacing, measuring and simulating the coal mechanical performance, and so on. After carrying out the simulations of conical pick cutting, the chip formation of coal and cracks, expansion in coal, the cutting force, and the number of cracks with different face and butt cleat spacing in the cutting process are analyzed. The detailed treatment method and the whole paper’s flowchart are shown in Figure 1.

2. Analyzing the Cutting Process of Conical Pick

2.1. The Structural and Working Principle of Shearer. Shearers are mainly composed of haulage units, rocker arms and drums, etc. The haulage unit provides traction for the whole device and helps the rocker arm up and down. The rocker arms, driven by motors, transmit rotating power to the drums. Mounted on the shearer’s drum, the conical picks cut coal directly under the rotary motion of the drums and the traction motion of the shearer during the process of shearer’s operation as shown in Figure 2.
2.2. The Cutting Process of Conical Pick. According to the working principle of the shearer, the cutting process of any pick can be simplified as shown in Figure 3. A coordinate system $xoy$ is fixed on the drum axis and $o'$ is the axial position of drum at the end of one cutting process of conical pick. $\gamma$, $\omega$, $v$, and $R$ are the installation angle of conical pick, drum angular velocity, shearer's traction speed, and cutting radius, respectively. $l$ and $s$ represent spacing of face and butt cleats, respectively. $T_1$ and $T_2$ are the long cycloidal cutting trajectories of conical pick before and after cutting, which can be calculated by equations (1) and (2), respectively, when $k=0$. The area surrounded by $T_1$ and $T_2$ is the cutting layer and $h_{max}$ is the maximum cutting depth.

\[
\begin{align*}
  x &= vt + R \sin \omega t, \\
  y &= R \cos \omega t, \\
  k &= (0.1 \ldots), \\
  T &= \frac{2\pi}{\omega} \\
  x'' &= \frac{H}{m} + vt + R \sin \omega t, \\
  y'' &= R \cos \omega t, \\
  H &= \frac{2\pi v}{\omega},
\end{align*}
\]

where $H$ represents the feed rate in one revolution and $m$ represents the number of conical picks on the same section line of the drum and is assumed as 1.

2.3. The Cutting Parameters of Conical Pick. The empirical cutting parameters of shearer are formed according to the mining environment and other working condition requirements [23]. In light of the empirical cutting parameters of sheers, the cutting parameters of conical pick are selected in this paper and shown in Table 1. To adapt the cutting radius $R$ and process, the size of coal is set as 800 mm in length and 1300 mm in height.

### Table 1: The cutting parameters of conical pick.

| Traction speed (m/s) | Drum angular velocity (rad/s) | Cutting radius (m) | Installation angle (°) |
|---------------------|-------------------------------|-------------------|------------------------|
| 0.07                | 5.76                          | 0.5               | 45                     |

2.4. The Cleat Spacing of Coal. There are three groups of cleats in coal, two groups of butt cleats perpendicular to each other and perpendicular to the third group of face cleats.

### Table 2: Cleat spacing of coal.

| No. | Face cleat spacing (mm) | Butt cleat spacing (mm) |
|-----|-------------------------|-------------------------|
| 1   | 130                     | 150                     |
| 2   | 150                     | 150                     |
| 3   | 170                     | 150                     |
| 4   | 150                     | 130                     |
| 5   | 150                     | 170                     |
Generally, the groups of face cleats always traverse the whole coal at an inclination angle of about $0^\circ$ [24], and the groups of face and butt cleats distribute in different spacing and obey the statistical distribution law [25]. The working face of the shearer is considered an approximately rectangular section divided by the groups of face and butt cleats in this paper. According to the face and butt cleat distribution law [26], 5 sets of the cleat spacing of coal were selected and are shown in Table 2.

| Density of particle (kg·m$^{-3}$) | Radius range of particles (mm) | Young’s modulus of particles (MPa) | Ratio of normal and tangential stiffness coefficient | Friction coefficient of particles |
|----------------------------------|-------------------------------|-----------------------------------|-----------------------------------------------|---------------------------------|
| 1800                             | 1.6–2.6                       | 3e9                               | 1.1                                           | 0.6                             |

| Tensile strength (MPa) | Cohesion (MPa) | Internal friction angle (°) | Stiffness ratio |
|------------------------|----------------|-----------------------------|-----------------|
| 52e6                   | 28e6           | 30                          | 1.1             |

![Figure 5: The stress-strain curves from simulations and tests.](image)

![Figure 6: The simulation process of the triaxial compression test.](image)
3. Establishment of the Coal Cutting Model of Conical Pick

3.1. Acquisition of Coal Mechanical Performance Simulation Parameters. A mass of coal in this research was collected from Jining Xinhe Mine in China and made as the coal specimens with a diameter of 50 mm and height of 100 mm. The triaxial compression tests of coal specimens are carried out by a servo control system of MTS815.03 under confining pressure of 10 and 20 MPa, respectively. The stress-strain curves are shown in Figure 4.

To obtain the property parameters of coal for establishing the cutting models, the particle flow program is written and debugged with the Fish language, which is embedded in PFC, to simulate the triaxial compression tests of coal specimens. For the smaller radius of coal particles, the more real generated model can truly reflect the mechanical properties of coal specimens and if the radius of particles is too small, there will be too many particles to simulate efficiently, and the radius range of coal mass particles is set as 1.6–2.6 mm in this paper [26]. The contact mode between coal particles is selected as the parallel bond model [27]. The density, Young’s modulus of coal, and other

| Normal stiffness (MPa·m⁻¹) | Tangential stiffness (MPa·m⁻¹) | Friction angle (°) | Bonding strength (MPa) | Bonding cohesion (MPa) |
|---------------------------|-------------------------------|-------------------|------------------------|-----------------------|
| $4\times10^4$             | $4\times10^1$                 | 12                | 0                      | 0                     |

Figure 7: The conical pick profile parameters.

Figure 8: The PFC model of the conical pick cutting coal.
micromechanical parameters of coal mass are shown in Table 3 [28].

To make the stress-strain curves from the simulation tests consistent with which from the tests, the bond parameters of coal were adjusted repeatedly, then the bond parameters of coal were obtained and shown in Table 4. The stress-strain curves from the simulation tests are almost consistent with which from the tests, as shown in Figure 5. The original state of coal specimen and the crack formation stage of initiation, expansion, and transfixion in the coal specimen in the simulation process of 10 MPa confining pressure are shown in Figures 6(a)–6(d), respectively.

3.2. The Generation and Mechanical Properties of Cleats. For the rock with complex structure, the SRM (synthetic rock mass) method was proposed to build the rock structure model [29], and various rock models were established and validated by comparing microseismicity, fragmentation, and yielding in SRM samples based on the SRM method in PFC [30, 31]. According to the SRM method, the coal mass, cleats, and contact between the coal mass and cleats are simulated by BPM (bonded particle model), DFN (discrete fracture network), and SJM (smooth joint model), respectively, in this paper. The mechanical properties of cleats are shown in Table 5 [32].

Figure 9: The dynamic cutting process of Figure 6(b).
3.3. The Process of Conical Pick Cutting Coal Model.
During the process of establishing models in PFC, the macro geometric structures of coal are regenerated by coal mass particles based on the micromechanical parameters, respectively, in Tables 3 and 4; the cleats are built based on the cleat spacing of coal in Table 2 and the parameters of mechanical properties of cleats in Table 5. The cutting trajectories are calculated with formula (1) based on the cutting parameters in Table 1.

Figure 10: The cutting force with various cleat spacing of Figure 6.
A ladder-shaped conical pick (U94) is selected as the model prototype, whose parameters are shown in Figure 7. Importing the model of conical pick into PFC, the coal cutting models are completed as shown in Figure 8. Figures 8(a)–8(e) represent the cutting model with the cleat spacing of No. 1–5 in Table 2, respectively, and blue color represents coal particles, and the green horizontal and vertical lines represent face and butt cleats.

4. Simulations

4.1. Cutting Coal Process of Conical Pick. When the conical pick cuts coal with the cutting parameters in Table 1, the dynamic simulations of the conical pick cutting process in Figures 8(a)–8(e) are carried out and they are similar. The cutting process of Figure 8(b) is taken as an example to analyze the dynamic process of the conical pick cutting coal. The dynamic process is shown in Figure 9.

Figures 9(a)–9(i) show the conical pick at the moment of contacting and cutting the coal with 25°, 50°, 75°, 90°, 115°, 140°, 165°, and 180°, respectively. Blue, green, and red colors in Figure 8 represent coal particles, tensile cracks, and shear cracks, respectively.

According to Figure 9(a), at the moment of the conical pick contacting coal, there is no formation and caving of coal chips. When the conical pick rotationally cuts to 25°, as shown in Figure 9(b), a few of the coal chips begin to form. When the conical pick comes to the period of 50°–90° as shown in Figures 9(c)–9(e), a lot of lumped coal chips gradually form and fall off, and the cleats near the conical pick tend to fracture. When the conical pick is in the period of 115°–180° as shown in Figures 9(f)–9(i), the cleats near the conical pick grow to be more obvious fractures, some lump coal chips fall off along the direction of the fractures, and most lump coal chips collapse along the motion direction of the conical pick.

The above dynamic processes of conical pick cutting coal are in accord with the actual cutting process and agree with the cutting simulation in the literature [6, 30]. Therefore, the establishment of conical pick cutting coal model is relatively reasonable in this paper.

According to Figure 9(a), at the moment of the conical pick contacting coal, a few shear and tensile cracks appear around the tip of the conical pick. With the continuous rotary cutting of the conical pick, as shown in Figures 9(b)–9(i), a large number of cracks are accumulated, and the number of tensile cracks is more than that of shear cracks in the whole cutting process.

The relationship between the cumulative number of tensile and shear cracks in this paper shows the fracture mechanism and movement direction of coal mass particles, which strengthen and prove the rationality of the results on coal cutting state [33].

4.2. Cutting Force of Conical Pick. The cutting force of conical pick with various cleat spacing of No. 1–5 is shown in Figures 10(a)–10(e), respectively.

According to Figure 10, it can be clearly seen that there is a large cutting force impulse, whose amplitude is more than 4 kN, at the moment of contact between the conical pick and coal. This phenomenon is probably due to the simulations based on single pick cutting. While in the actual cutting process, there are multiple picks on the drum to participate in cutting at the same time, this will balance part of the impact force. In the following cutting process, the cutting force, accompanied by irregular fluctuations, changes with the change of cutting thickness.

It can be seen that the cutting force decreases clearly when the conical pick cuts to around 50° and 160° in Figure 10(b). Comparing Figures 10(b), 9(b), and 8, it can be speculated that the obvious decrease of cutting force may be due to the intersection of the face and butt cleats leading to a decrease of coal strength.

Neglecting the large amplitude impulse of cutting force at the moment of contacting between the conical pick and coal, the mean, peak, and maximum fluctuations of cutting force are counted in Table 6. According to the data of No. 1, 2, and 3 in Table 6, it can be seen that the mean and maximum fluctuations of cutting force increase with the increase of face cleat spacing. However, the peak cutting force does not obey this law and shows irregularity and randomness. From the data in Table 6 (No. 4, 2, and 5), it can be found that the mean and maximum fluctuations of cutting force increase with the increase of butt cleat spacing in the cutting process, and the maximum cutting force shows an irregular trend. Comparing the data in Tables 2 and 6, it can be seen that the face cleat spacing has a greater influence on the conical pick cutting force than that of butt cleat spacing. In other words, the increment of face cleat spacing leads to greater cutting force than that of butt cleat spacing.

4.3. Number of Crack Accumulation. The number of tensile and shear crack accumulation in the cutting process with various cleat spacing of No. 1–5 is shown in Figures 11(a) and 11(b), respectively. According to Figure 11, it can be seen that the number of tensile and shear cracks increases approximately linearly in the process of conical pick cutting coal, and the number of tensile cracks is more than twice that

| No. | The mean cutting force (kN) | The peak cutting force (kN) | The maximum fluctuation of cutting force (kN) |
|-----|-----------------------------|-----------------------------|---------------------------------------------|
| 1   | 0.450                       | 1.812                       | 0.898                                       |
| 2   | 0.466                       | 1.632                       | 0.938                                       |
| 3   | 0.503                       | 1.944                       | 1.041                                       |
| 4   | 0.442                       | 1.803                       | 0.867                                       |
| 5   | 0.473                       | 1.754                       | 0.963                                       |
of the shear cracks in the whole cutting process except at the moment of the conical pick contacting coal. This is consistent with the conclusion that the main cracks are tensile cracks and the initiation and expansion of tensile cracks are the main reasons of coal damage [33].

According to Figure 11(b), it can be seen that the orders of the number of tensile and shear cracks from large to small are all No. 5-3-2-1-4. By analyzing the data of cleat spacing of coal in Table 1, it can be found that the lower the density of cleats, the more the cracks. The accumulation numbers of tensile and shear crack numbers are counted in Table 7.

According to Table 7 (No. 1, 2, and 3), the number of cracks with different face cleat spacing trend can be obtained so that the number of the tensile and shear cracks increases with the increase of face cleat spacing. According to Table 7 (No. 4, 2, and 5), the trend of crack number with different butt cleat spacing can be achieved so that the numbers of tensile and shear cracks increase with the increase of butt cleat spacing.

By comparing the data in Tables 2 and 7, it can be found that the face cleat spacing also has a greater influence on the crack number than butt cleat spacing.

5. Conclusions

In this paper, the influence of coal cleats on the conical pick cutting process is studied. The coal cutting models with various cleat spacing are established based on the SRM method in PFC, and the rotary cutting coal process of conical pick is simulated. Some conclusions are obtained as follows:

(1) During the rotary cutting coal process of conical pick, the formation of coal chips is from scratch, and from small to lump, the lump coal chips begin to form after the conical pick cuts to 50° and the cleats near the conical pick grow to be more obvious fracture, some lump coal chips fall off along the direction of fractures, and most lump coal chips collapse along the motion direction of the conical pick.

(2) The mean and maximum fluctuations of cutting force increase with the increase of face and butt cleat spacing; however, the peak cutting force shows an irregular trend. The lower the density of cleats is, the more the cracks are formed during the cutting process. The face cleat spacing has a greater influence on the cutting process of conical pick than that of butt cleat spacing.

(3) Neglecting at the moment of contact between the conical pick and coal, the number of tensile cracks is more than twice that of the shear cracks in the entire cutting process.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.
Conflicts of Interest

The authors declare that they have no conflicts of interest.

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