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Rock cutting characteristics with single pick and prediction of cutting force based on force chain

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Abstract: The pick is the main load-bearing object of the mining machinery for cutting coal. Prediction of the cutting force from the working condition is essential to reduce the wear of the pick. The rock was considered as a granular material for single pick cutting simulation using the particle flow code (PFC^{2D}). The influence of the contact state on the cutting force of the single pick was discussed based on the characteristics of the force chain between particles during rock cutting. The cutting force test was carried out with a single pick cutting test equipment. The variation laws of the cutting normal and tangential forces with cutting parameters and the characteristics of falling fragments were obtained. The research results show that the relationship between the number and length of force chains for cutting rock particles with a single pick is consistent with the results of uniaxial compression test in laboratory, demonstrating that the discrete element method can be used to simulate the cutting state of the single pick. The force chain network spreads and extends along the point contact direction, which is related to the cutting angle. The average normal force direction is "peanut"-shaped whereas the tangential force direction is "petal"-shaped. The number of force chains decreases with the decrease of cutting angle and the increase of cutting depth. The length of force chains increases with the increase of cutting distance. The maximum average length is about 8 times the particle size. When the cutting angle is larger, it is easier to form a force chain. The normal and tangential forces of single pick cutting of natural sandstone decrease with the increase of the cutting angle and the decrease of the cutting depth. The coefficient of determination for linear correlation between the size of the cutting fragments and the cutting tangential force is 0.87. Compared with the Evans model, the cutting force prediction model based on the length of force chain improves the accuracy of the normal force by 17.6% and the accuracy of the tangential force by 16.9%. The research results could lay a certain research foundation for the design of cutting pick, mining machinery cutting system and the optimization of cutting technology.

Keywords: granular material; single pick cutting; force chain; force prediction

1 Introduction

As one of the indispensable part in the cutting system of underground roadway driving and mining machinery, pick directly bears the fracture load of rock or coal. During rock breaking, the pick cuts and crushes the coal under large thrust, and its interaction with the coal produces intense friction and extrusion. The cutting force of the pick is one of the principal factors during the design of the cutting system[1]. Therefore, accurate prediction and evaluation of pick cutting force is extremely necessary for the design and manufacture of pick and cutting system.

Numerous scholars have managed to propose novel theoretical models[3–5] or test models[6–9] for predicting the cutting force since Evans[2] built the theoretical model based on the maximum tension criterion in 1984. These models generally calculate the peak cutting force based on the elasto-plastic theory or fracture mechanics theory. In 2018, Li et al.[10] elaborated the typical theoretical models for calculating the cutting force. Due to the nonlinear physical properties of the coal, and the mechanical discontinuity of the cutting process, these available theoretical calculation models differ greatly and have not yet reached a consensus. To this end, further investigations should be focused on the calculation accuracy and practicability of the pick cutting force model.

The relatively mature conventional rock cutting theories generally treat the objects to be cut such as rock or coal as a continuum, which is different from the intrinsic properties of rock or coal. With the development of particle physics and mechanics, the study of rock cutting should be changed from a continuous system to a more accurate particle system, which involves a relatively complex energy dissipation system. The contact force between particles is generally transmitted along a chain-like path, commonly known as force chain, forming a multi-scale structure of particle → force chain → system[11–12]. Through analyzing the instability and reconstruction of force chain structure, the overall mechanical behaviors of rock can be further understood[13], which plays an important role in studying the dynamic behaviors of pick cutting. In addition, research findings based on fracture mechanics also manifest that the cutting force is related to the initiation

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and propagation of cracks[14]. Therefore, it is necessary to establish a rock breaking model based on particle physics and mechanics to analyze the mesoscopic mechanical properties of coal with force chain as the characteristic scale, which will be more close to the reality.

In 2005, *Science* listed granular material and turbulence as one of the 125 scientific questions[15], to which field many scholars have devoted themselves. Ebrahimabadi et al.[16] observed the evolution of rock failure under point contact, and thus the existence of force chains in rock and soil has been confirmed. Saadat et al.[17] took the rock as granular material and studied the mechanical effect of bolt anchored in rock. Huang et al.[18–19] treated the coal as granular material to simulate the fully mechanized mining with mechanized backfilling, and studied the roof's force chain change, collapse and stress distribution in backfilling under different filling rates and slope gradients. Based on the continuum-discontinuum element method (CDEM), Xiao et al.[20] established a three-dimensional (3D) simulation method for milling rock and soil masses with milling wheels. Due to the limitations of test conditions, some scholars adopted particle flow simulation to obtain the variables affecting force chain and the parameters describing the magnitude and direction of the force chain[21]. These studies have laid the research foundations for applying particle flow method to simulate the cutting process of rock or coal.

To sum up, in order to establish a more precise cutting force prediction model, this paper develops a particle flow model for calculating the pick cutting force in rock, and obtains the calculation method for the peak cutting force of single pick in natural sandstone. Based on the number, length and direction of force chains of rock particle system during single pick cutting, the variation of force chain with cutting parameters under point contact is revealed. The physical test results of single pick cutting natural sandstone verify the proposed cutting force prediction model based on force chain characteristics, and the calculation accuracy has been improved compared with the calculation models based on the conventional fracture mechanics.

2 Prediction model and simulation method for single pick cutting force

2.1 Mathematical expression of single pick cutting force

The mathematical model of single pick cutting established by Evans[2] is considered as the foundation of the other theoretical models, and it can be written as follows:

$$\mathrm{PCF_{Ev}} = \frac{16\pi\sigma_t^2 d^2}{\sigma_c \cos^2\alpha} \tag{1}$$

where σ_t and σ_c are the Brazilian tensile strength and uniaxial compressive strength of the rock, respectively; d is the cutting depth; α is the half angle of the pick, which is related to the shape of the pick and the cutting angle; and $\mathrm{PCF_{Ev}}$ is the peak cutting force calculated by the Evans model.

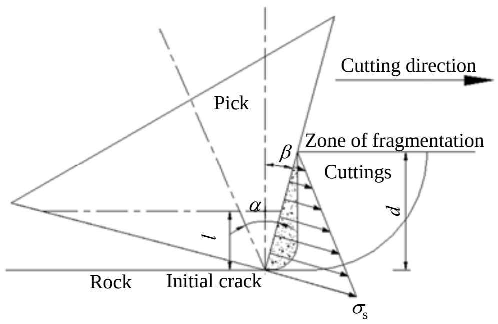


Fig. 1 Schematic diagram of calculation of pick cutting force[10]

Despite being widely used in the engineering, the Evans model has following limitations. For example, the pick has to be perpendicular to the rock and the cutting force must be inversely proportional to the uniaxial compressive strength. These conditions are appreciably harsh in practical application. To solve these problems in the model, Goktan et al.[22–23] put forward the improved models, but these models focused more on the process of pick pressing into the rock rather than the cutting state of the pick. In addition, Griffith fracture theory should also be considered to establish the calculation model of cutting force. Based on the above analysis, Li et al.[10] proposed a relatively mature and reliable calculation method for peak cutting force of a single pick:

$$\mathrm{PCF_{Li\,X}} = \int_0^d \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \sigma\cos\theta\cdot r\mathrm{d}\theta\mathrm{d}l = \int_0^d \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \left[\frac{2}{\pi}\left(\frac{\sin\alpha}{\cos\beta}-1\right)\theta+1\right]\cdot \frac{(d-l)K_{IC}}{d\sqrt{\pi\delta}}\cos\theta\cdot\lambda l\mathrm{d}\theta\mathrm{d}l = \frac{\lambda K_{IC} d^2}{3\sqrt{\pi\delta}} \tag{2}$$

where l is the vertical distance between a given point on the generatrix and the pick tip; σ is the stress at the position angle θ of the pick profile; r is the radius of the pick profile; β is the anterior angle of the pick; K_{IC} is the Mode I fracture toughness of the rock; δ is the crack length; $\mathrm{PCF_{Li\,X}}$ is the peak cutting force of the single pick calculated by Li et al.[10], as shown in Fig. 1, in which σ_s is the critical stress for crack initiation; and λ is a coefficient related to the pick shape and cutting angle, and it is written as

$$\lambda = \frac{\tan(2\alpha-|\beta|+\tan|\beta|)}{4} + \frac{1}{2}\tan\alpha\left[\frac{\tan(2\alpha-|\beta|-2\tan(\alpha-|\beta|)-\tan|\beta|}{2}\cdot \sin(\alpha-|\beta|)+\frac{1}{\cos(\alpha-|\beta|)}\right. \tag{3}$$

According to Eq. (2), the peak cutting force of a single pick is negatively correlated with the crack length. Therefore, the cutting force reaches the maximum value when the cracks initiate, and decreases gradually with crack propagation. After the rock is fragmented, the cutting force decreases to zero, followed by the generation of new sets of cracks, accounting for the drastic fluctuations in the cutting force of driving or mining machinery.

The crack size δ determines the cutting force of a single pick, but it is difficult to be measured before the rock is broken. To this end, previous experiences resorted to the conservation law of energy. In this paper, the particle flow method is used to acquire the characteristic parameters of the force chain instead of the crack size.

2.2 Particle flow model of single pick cutting

To examine the impact of single pick cutting parameters on rock breaking and the prediction of cutting force, a point-contact particle flow model is built using PFC^{2D} in this study, as shown in Fig. 2. A natural sandstone is selected as the test object. The mechanical properties of the rock can be found in the study of Zhang et al.[24], and the macroscopic characteristics are listed in Table 1. To facilitate the comparison between the subsequent simulation results and the physical test results, the particle flow model adopts the consistent characteristic parameters of sandstone. There is no clear correspondence between the mesoscopic properties of granular material and the macroscopic properties of rock. Hence, with the purpose of simulating the characteristics of rock mixtures as much as possible, the uniaxial compression and tension tests of rock are carried out to determine the stress-strain characteristics, and then the mesoscopic parameters of granular material are calibrated accordingly. The calibration method has been well documented in the literature[25–26]. During calibration, the Young's modulus and the ratio of normal stiffness to tangential stiffness of contact between particles are adjusted. Once the numerical result is consistent with the test value, the simulation model basically conforms to the test material. The calibrated mesoscopic parameters of rock particles are listed in Table 2. The particle model adopts the flat joint contact model, which has a large tension-to-compression ratio. It can mitigate the problem of small friction angle between particles and reduce the particle rotation frequency. Hence, it is applicable to the simulation of rock particles. The uniaxial tension and compression test results are shown in Fig. 3. The size of the developed two-dimensional (2D) rock particle model is 150 mm × 150 mm, accommodating 31 002 spherical particles.

As mentioned above, the state parameters of the pick–rock interface have a great influence on the cutting force and rock breaking rate. Therefore, the particle flow simulation test and the single pick cutting physical test are designed, to explore the relationship between the cutting parameters and the force chain of rock particles, as listed in Table 3. The cutting angles are selected as 44°, 48° and 52°, the cutting depths are 2 mm, 3 mm and 4 mm, and the cutting linear velocity is 2 m/s.

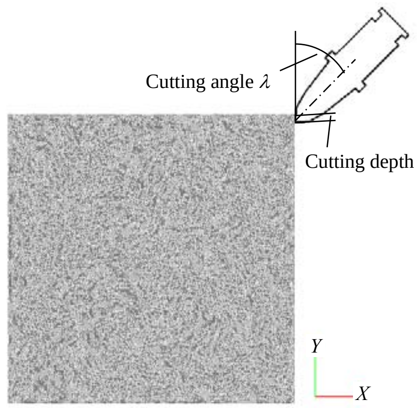


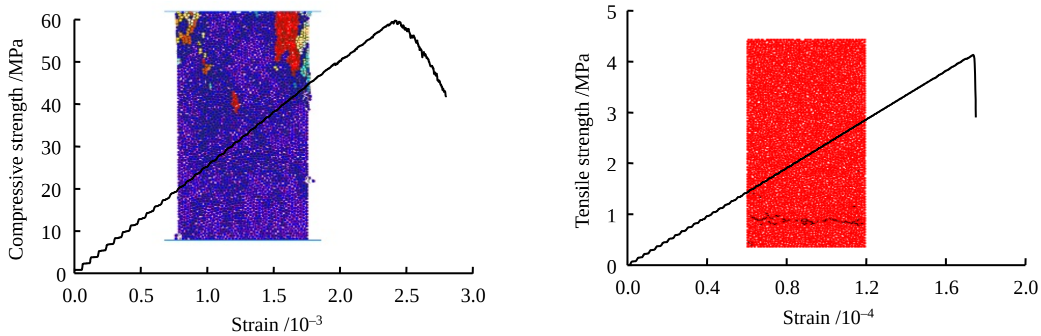
Fig. 2 Point-contact particle flow model for simulating rock cutting by a single pick

Table 1 Macroscopic parameters of rock[24]

Density ρ /(kg • m^{-3})	Compressive strength /MPa	Tensile strength /MPa	Young's modulus E /GPa	Poisson's ratio v
2 340	61.7	4	21	0.26

Table 2 Mesoscopic parameters of rock particles

Density ρ /(kg • m^{-3})	Radius of particles R /mm	Compressive strength /MPa	Tensile strength /MPa	Bond stiffness ratio k	Young's modulus E /GPa	Porosity	Coefficient of friction μ
1 660	0.5	33.2	5.23	1.5	20	0.12	0.3



(a) Compression test (b) Tension test

Fig. 3 Model calibration results

Table 3 Test conditions

Test No.	Cutting depth /mm	Cutting angle /(°)	Test No.	Cutting depth /mm	Cutting angle /(°)
1	2	44	6	3	52
2	2	48	7	4	44
3	2	52	8	4	48
4	3	44	9	4	52
5	3	48			

2.3 Criterion and algorithm of force chain

The exact definition of force chain is still under debate. Bi et al.[27] defined the directed line segment with large energy in the particle network as the force chain. Wang's group of Tsinghua University also gave the definition of force chain[12, 28]: The transmission path of the external load in the granular material at meso-scale, and the bridge between the macroscopic stress and microscopic intergranular forces. In other words, the size and direction of force chain are determined by the intergranular forces, and in turn determine the macroscopic mechanical properties of the system. The force chains consist of strong and weak chains, and they interlace with each other, forming a complex force chain network. The strong chain plays the decisive role in supporting load and bearing the particle system. Therefore, the main method to study the force chain of granular material is to systematically analyze the distribution characteristics of the strong chain. In this study, when not specified, the force chain refers to the strong chain. There are many factors influencing the force chain, including the physical properties of the particle material, the boundary conditions of the particle system and the load. In a particle flow model, the contact force between particles is calculated according to the Herts-Mindlin theory, and the derived normal and tangential forces are written as

$$\left.\begin{aligned} F_i^{\mathrm{n}} &= K^{\mathrm{n}}\Delta U_i^{\mathrm{n}} - \eta_{\mathrm{n}}\bar{v} \\ \Delta F_i^{\mathrm{t}} &= -K^{\mathrm{t}}\cdot\Delta U_i^{\mathrm{t}} - \eta_{\mathrm{t}}\Delta\bar{v}_{\mathrm{s}} \end{aligned}\right\} \tag{4}$$

where F_i^{n} and ΔF_i^{t} are the normal and tangential forces of the i-th particle under point contact; ΔU_i^{n} and ΔU_i^{t} are the normal and tangential displacement increments; η_{n} and η_{t} are the normal and tangential damping coefficients; $\bar{v}$ and $\Delta\bar{v}_{\mathrm{s}}$ are the relative velocity of particles and the slip velocity of contact points; and K^{n} and K^{t} are the normal and tangential contact stiffnesses of particles, and they are determined by

$$\left.\begin{aligned} K^{\mathrm{n}} &= \left[\frac{2\tilde{G}\sqrt{2\tilde{R}}}{3(1-\tilde{v})}\right]\sqrt{U_i^{\mathrm{n}}} \\ K^{\mathrm{t}} &= \left[\frac{2(\tilde{G}^2 3(1-\tilde{v})\tilde{R})^{1/3}}{2-\tilde{v}}\right]\left|F_i^{\mathrm{n}}\right|^{1/3} \end{aligned}\right\} \tag{5}$$

where $\tilde{G}$ and $\tilde{v}$ are the equivalent shear modulus and equivalent Poisson's ratio; and $\tilde{R}$ is the equivalent radius of the particle.

The flow chart for searching force chains is shown in Fig. 4, where P represents the number of particles with any high-stress particle as the starting point of the force chain, and the initial value is set to 1. Firstly, the contact and stress information of all particles in the system is collected, and then those particles with less than or equal to the average stress are filtered out using the equation below[29]:

$$\sigma > \frac{1}{N}\sum_{i=1}^{N}\left|\sigma_3^i\right| \tag{6}$$

where N is the total number of particles in the model; and σ_3^i is the minimum principal stress of the i-th particle.

The maximum and minimum principal stresses of the point-contact granular material are written as

$$\sigma_1 = \frac{\sigma_{11}+\sigma_{22}}{2} + \sqrt{\left(\frac{\sigma_{11}-\sigma_{22}}{2}\right)^2 + (\tau_{12})^2} \tag{7}$$

$$\sigma_3 = \frac{\sigma_{11}+\sigma_{22}}{2} - \sqrt{\left(\frac{\sigma_{11}-\sigma_{22}}{2}\right)^2 + (\tau_{12})^2} \tag{8}$$

where σ_1 and σ_3 are the maximum and minimum principal stresses, respectively; σ_{11} and σ_{22} are the stresses in two directions perpendicular to each other; and τ_{12} is the maximum shear stress in these two directions. All of them are negative (compressive stress), and the absolute value of the minimum principal stress is used as the basis for calculating the average stress. The angle of the force chain is determined by the following criterion that whether the included angle θ between the central line of the adjacent particles and the direction of the minimum principal stress is less than θ_{c} [30]:

$$\cos\theta_{\mathrm{c}} < \frac{\left|\boldsymbol{L}\sigma^{\mathrm{next}}\right|}{\left|\boldsymbol{L}\right|\left|\sigma^{\mathrm{next}}\right|} = \cos\theta \tag{9}$$

where σ^{next} is the minimum principal stress of the adjacent particles; L is the vector connecting the particle centroids; θ_{c} is the change threshold of the particle centroid connection angle, which is related to the geometrical structure of the contact surface such as occlusion and embedding.

The value of θ_{c} is related to the contact state between particles, and also affects the length and probability density of the force chain. Currently, θ_{c} is generally determined by the average coordination number of the particle system since there is no unified standard:

$$\theta_{\mathrm{c}} = \frac{180^\circ}{z} = \frac{N\times 180^\circ}{2N_{\mathrm{c}}} \tag{10}$$

where z is the average coordination number between particles; and N_{c} is the actual number of contacts between particles.

When the direction of contact force θ of two high-stress particles is less than or equal to θ_{c}, the contact force between them is considered to be a force chain, and the direction of contact force is taken as the angle of force chain.

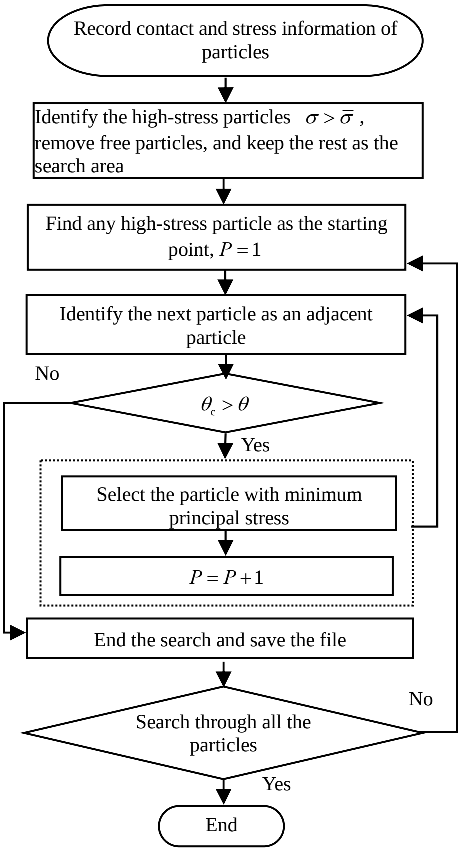


Fig. 4 Flow chart for searching force chains

In the new cutting force prediction model, the force chain length n is defined as[12]

$$n = \sum_{i=1}^{N_c} \frac{d_i}{\langle d \rangle} \tag{11}$$

where d_i is the particle size of the force chain; $\langle d \rangle$ refers to the average particle size of the particle system, thus the length of force chain is the number of particles on it.

In the proposed single pick cutting force method based on force chain characteristics, the crack size δ in Li model[10] is written as

$$\delta = \sum_{i}^{N} \frac{n_i}{NL} \tag{12}$$

where δ is the average length of force chain under unit cutting distance and number of force chains; N is the number of strong chains; L is the cutting distance; and n_i is the length of strong chain. The force chain length parameter δ is substituted into Eq. (2) as the crack size, and the final cutting force prediction model is derived:

$$\mathrm{PCF}_{\mathrm{Lilian}} = \sum_{i}^{N} \frac{\lambda K_{\mathrm{IC}} d^2}{\sqrt[3]{\frac{\pi n_i}{NL}}} \tag{13}$$

where $\mathrm{PCF}_{\mathrm{Lilian}}$ is the peak cutting force of a single pick based on force chain characteristics.

3 Rock force chain characteristics under single pick cutting

3.1 Model validation

In order to validate the particle flow model, corresponding length and number of force chains were extracted when cutting 5 mm each time. The relationships between the length and number of force chains in the simulation model are presented in Fig. 5. Fig.5(a) shows the relationships between the length and number of force chains at different cutting angles under 3 mm cutting depth, and Fig. 5(b) shows their relationships at different cutting depths when the cutting angle is 48°.

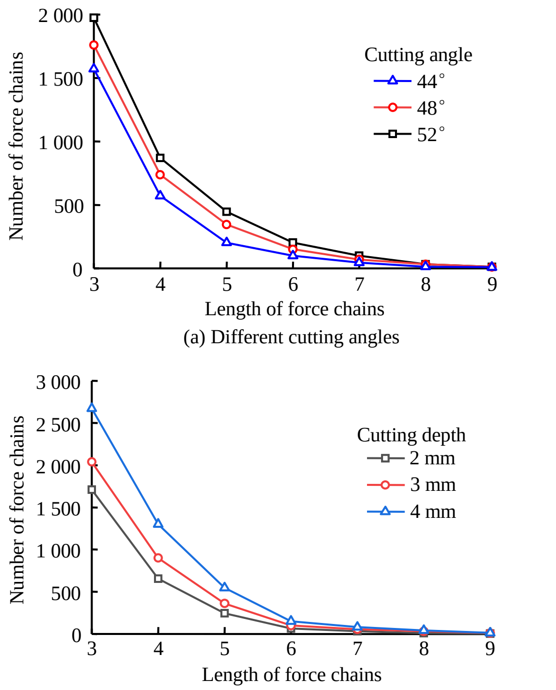
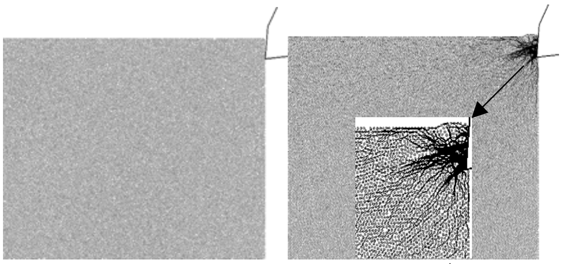


Fig. 5 Relationships between the length and number of force chains

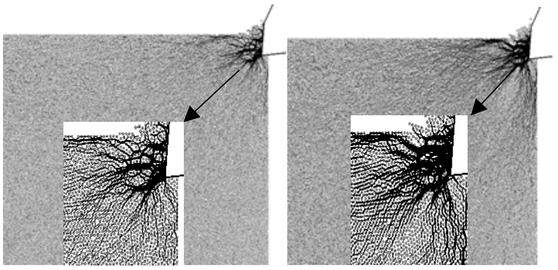
As shown in Fig. 5, the length and number of force chains is inversely distributed, regardless of the test conditions, which is consistent with the conclusion from the literature[31]. This finding suggests that the relationship between the length and number of force chains of granular material under point contact is consistent with the uniaxial compression test results Meanwhile, it also verifies the feasibility of the simulation model.

3.2 Relationship between single pick cutting state and force chain

Figure 6 depicts the force chain evolution with cutting time during rock cutting by a single pick. With the increase of cutting time t, the number of force chains increases gradually, and the length of force chains also increases slightly. The force chain network spreads and extends along the point contact direction. With the further increase of cutting time, the force chain network constantly breaks and reconstructs, and reaches a relatively stable state eventually.



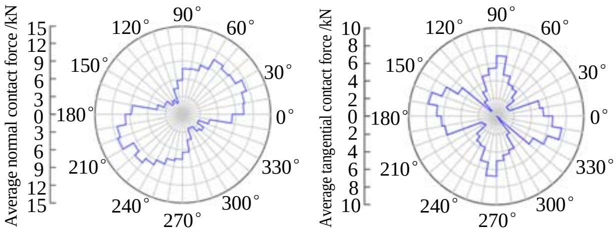
(a) t=0 s (b) t=5×10^{-4} s



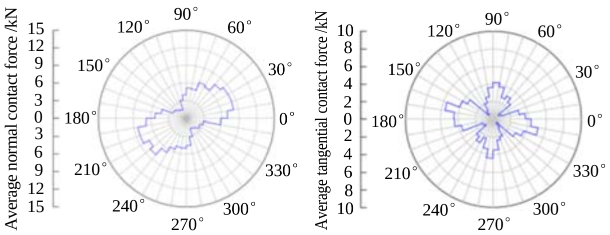
(c) t=1×10^{-3} s (d) t=1.5×10^{-3} s

Fig. 6 Evolution of force chain network with cutting time

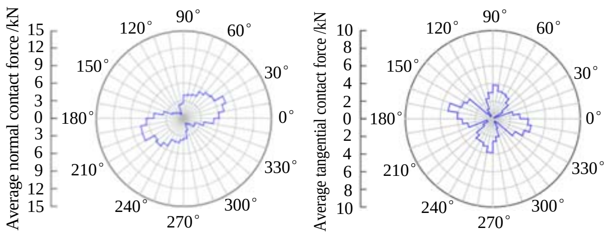
To figure out the relationship between the direction of force chain and cutting angle, the variation of the direction of force chain for single pick cutting with cutting angle is studied, as shown in Fig. 7.



(a) Cutting angle of 44°



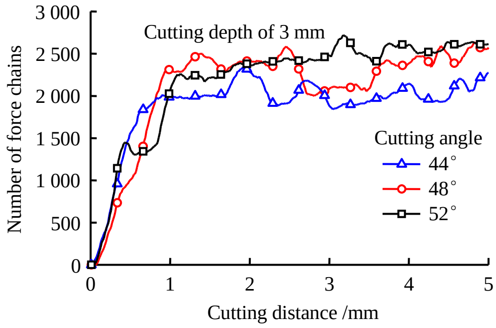
(b) Cutting angle of 48°



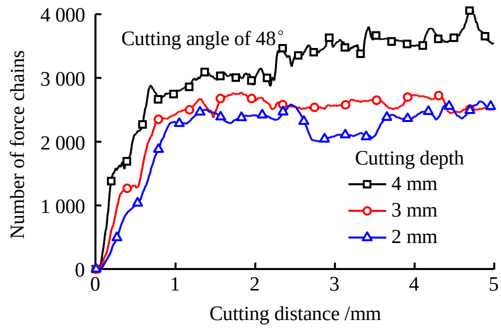
(c) Cutting angle of 52°

Fig. 7 Relationships between contact force direction of force chains and cutting angle

One can see that the direction of the average normal contact force of the force chain is closely related to the cutting angle, showing a "peanut" shape along the cutting angle, similar to the conclusion of Zhou et al.[32], although the direction of contact force is slightly smaller than the cutting angle. This is due to the combined effect of internal friction and shear force between the particles. Therefore, the influence of shear band of granular material on the direction of granular material force chain cannot be ignored. By contrast, the tangential force direction of the force chain is "petal"-shaped, with the angles of 85°, 165°, 265° and 345°. The average contact normal and tangential forces both increase with the decrease of cutting angle. Note that the cutting method adopted in this study is different from those in the literature[32–33], but the similar results are obtained, indicating that the evolution of force chain direction of granular material under point contact or point-like contact is independent of the motion mode of rigid body at the contact interface.



(a) Different cutting angles

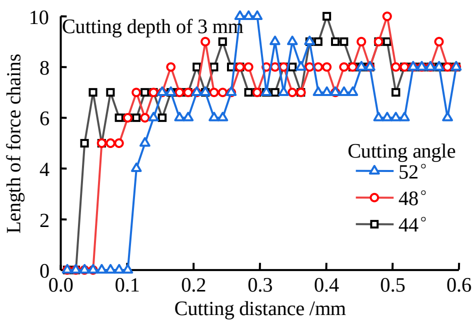


(b) Different cutting depths

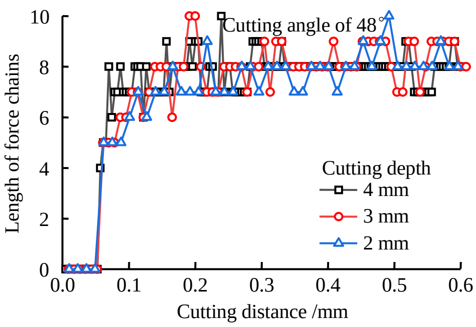
Fig. 8 Relationships between cutting state of a single pick and number of force chains

A thorough investigation into the relationship between the single pick cutting state and the force chain is conducted. The variation law of the number of force chains with cutting distance under different cutting angles and depths is shown in Fig. 8. The change curves of the number of force chains with cutting distance are plotted in Fig. 8(a) (at 3 mm cutting depth but different cutting angles) and Fig. 8(b) (at 48° cutting angle but different cutting depths). As can be seen, with the increase of cutting distance, the number of force chains basically increases logarithmically, indicating that the number of force chains can characterize the cutting state to a certain extent. The number of force chains is less at smaller cutting angles and larger cutting depths, indicating that the particle state is destroyed before the formation of force chains, and thus the rock breaking rate is improved. Therefore, if conditions permit, reducing the cutting angle and increasing the cutting depth can positively affect cutting efficiency, which offers a new idea for further research on the cutting process of driving or mining machinery and the design of cutting system.

The cutting force of a single pick generally increases with the increase of cutting distance. It tends to be stable when the pick completely enters rock particles, and then fluctuates violently around a fixed value. The relationship of the length of force chain with cutting distance during single pick cutting is illustrated in Fig. 9. Figure 9(a) is plotted with a fixed cutting depth (3 mm) but variable cutting angles, while Fig. 9(b) is plotted with different cutting depths but a fixed cutting angle (48°). It is clear that the length of force chain increases nonlinearly as the cutting distance increases. When the length of force chain increases to 8 particles, the force chain tends to be stable, even if the cutting distance further lengthens. The length of force chain approximately equal to 8 particles reflects that the strong chain is constantly destroyed and reconstructed with the increase of cutting distance. The "zigzag" pattern of the length of force chain is different from the change in the number of force chains in Fig. 8. The reason is that the number of force chains is instantaneous and constantly changes with the destruction and reconstruction of force chains, while the length of force chain is statistical, whose change is insensitive to the slight increase of cutting distance. In addition, it is universal that the length of force chain is no more than 9 times the particle size, no matter in the point contact form or the uniaxial/ biaxial compression form.



(a) Different cutting angles



(b) Different cutting depths

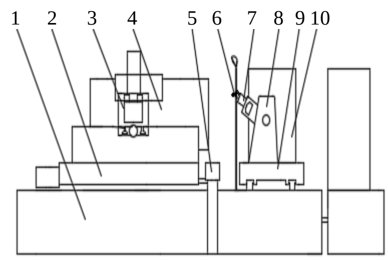
Fig. 9 Relationships between cutting state of a single pick and length of force chains

Figure 9(a) also reveals that under large cutting angle, the length of force chain reaches the maximum value first and approaches to the stable state forthwith. Since the cutting force stays low, the rock is less damaged. This finding further confirms that the cutting angle is more sensitive to the formation of force chains than the cutting depth.

4 Single pick cutting test

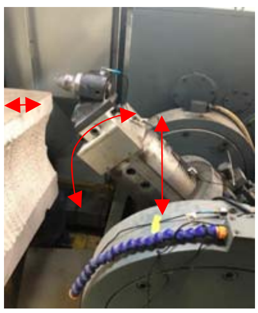
4.1 Test apparatus

The single pick cutting test machine at the National Engineering Laboratory of Coal Mining Machinery and Equipment is used, as shown in Fig. 10(a). The test machine is capable of simulating rock breaking process, and determining the cutting force, wear state and dust capacity of a single pick. The cutting angle, speed and depth of a single pick relative to the cutting object can be adjusted to obtain three-direction cutting force data, providing technical support for the design of pick and cutting system. The test machine is connected with an octagonal ring dynamometer and a multi-channel data acquisition system, which can monitor and collect the triaxial force in real time. The sampling frequency is up to 20 kHz. The pick can rotate and move forwards and backwards flexibly along the direction of the arrow, and the rock specimen is allowed to move left and right along the direction of the arrow, as shown in Fig. 10(b). The pick rotation speed determines the speed of the cutting line, the installation angle of the pick relative to the seat determines the cutting angle, the moving displacement of the pick back and forth determines the spacing of the cutting line, and the rock moving displacement determines the cutting depth. The implementation of the single pick cutting is accomplished by the relative motion between pick and rock.



1—Base fixing device; 2—Rock moving device; 3—Rock clamping device; 4—Rock specimen; 5—Test control system; 6—Pick; 7—Cutting force sensor; 8—Cutting actuator; 9—Cutter frame moving device; 10—Gearbox

(a) Sketch of single pick cutting machine



(b) Photo of cutting machine

Fig. 10 Single pick cutting machine

4.2 Test object

The test object was made of alloy steel (35CrMnSiA high-strength steel), with Vickers hardness of 862 HV, extension length of 80 mm, handle diameter of 38 mm, pick diameter of 25 mm, edge diameter of 60 mm, and pick tip angle of 80°. Pick holders with three angles were selected for the cutting test, as shown in Fig. 11. The test conditions are listed in Table 3. Each test was repeated three times, with a linear velocity of 2 m/s and a spacing of 20 mm. The ambient temperature of the test was set at 19 ℃, and the sampling frequency of the dynamometer was 500 Hz. A natural sandstone with the size of 1200 mm × 600 mm × 800 mm was used as the cutting object, whose main macroscopic properties are summarized in Table 1.

Fig. 11 Pick holders with different angles

4.3 Test results and discussion

For different cutting depths, the changes of cutting normal and tangential forces with cutting angle are displayed in Figs. 12(a) and 12(b), respectively. With the deepening of cutting depth, the normal and tangential cutting forces both increase. When the cutting angle increases, however, the normal and tangential cutting forces both decrease, and the normal force drops more dramatically. This probably because with the increase of cutting angle, the normal impact force acting on the rock decreases, while the shear force increases, and thus the fracture pattern changes from the original tensile failure to shear failure. This inference can be corroborated by the literature[34]. In order to further illustrate the influence of shear force on the performance of a single pick, falling fragments were collected for dimensional analysis, as shown in Fig. 13. It is found that the size of rock fragments increases with decreasing cutting angle, indicating that the pick plays a major role in the rock compressive stress when the cutting angle is larger. For the case of small cutting angle, the pick causes shear failure of rock. Moreover, the natural sandstone is more brittle, and the geometrical size of the fragments becomes larger and thinner. In Fig. 14, the linear regression between fragments size and cutting tangential force suggests that there is a specific linearity between them, and the coefficient of determination is 0.87. Therefore, appropriate cutting angle parameters should be determined according to different rock selection conditions.

4.4 Comparison between cutting force prediction model and laboratory test

In order to verify the peak cutting force prediction model for single pick based on force chain, Evans model, Li X model[10] and the force chain model proposed in this study are calculated, respectively. Meanwhile, the calculation results are compared with the test results to estimate the changes of peak normal and tangential forces with cutting parameters. A typical comparison of normal and tangential forces under 3 mm cutting depth is presented in Fig. 15, and the rules reflected are similar to the calculation results under other test conditions.

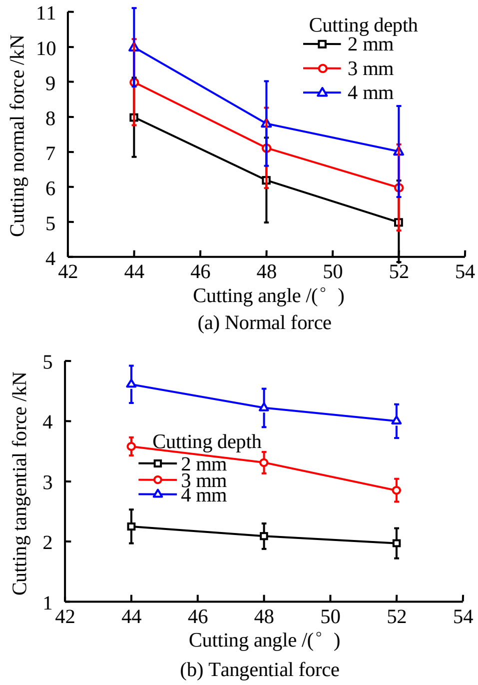


Fig. 12 Relationships between cutting force and cutting angle under different cutting depths

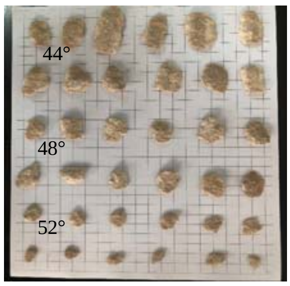


Fig. 13 Shape and size of rock fragments

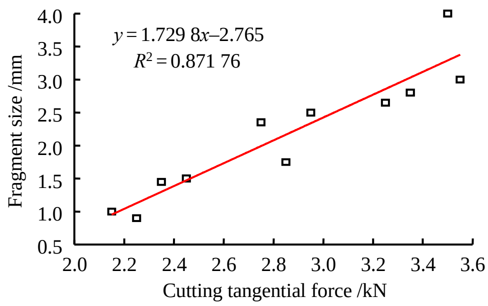
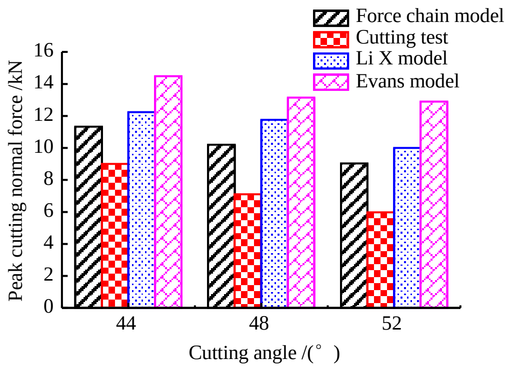
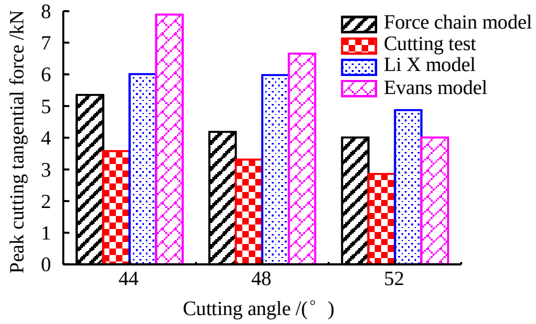


Fig. 14 Regression analysis of fragment size and cutting tangential force



(a) Comparison of normal force



(b) Comparison of tangential force

Fig. 15 Comparisons between calculation results of cutting force prediction model and laboratory test data

As shown in Fig. 15, the cutting forces obtained from the tests are generally lower than the theoretical calculation results. An inquiry into this question has found that, on the one hand, there are cracks and joints in the natural sandstone used in the test, whereas joints and faults are not considered in the simulation. On the other hand, there may be some errors in the calibration of rock macroscopic parameters. The changes of particle radius, friction coefficient, elastic modulus and other parameters will have a great impact on the cutting force.

According to the comparison between three calculation models in Fig. 15, the Evans model has the largest deviation from the test results of both normal and tangential forces, with the average deviation of normal force being 45.8% and the average deviation of tangential force being 44.6%. The force chain model has the lowest deviation, with the average deviation of normal force being 28.2% and the average deviation of tangential force being 27.6%. The accuracy of the normal and tangential forces of the force chain model is 17.6% and 16.9% higher than those of the Evans model, respectively, and also outperforms the Li X model. The innovation of this paper is to take the length of force chain as the crack size. It can not only predict the peak cutting force before the rock is broken subjected to single pick cutting, but also predict the crack growth state and fragment shape from the meso-scale, which provides a theoretical basis for the design and manufacture of pick and cutting system of tunneling or mining machinery.

5 Conclusions

In this study, the concept of force chain in particle mechanics is introduced into the cutting force prediction model for single pick. The simulation of single pick cutting is carried out using the particle flow code PFC^{2D}. The evolution of force chain network and the change of contact angle with time during single pick cutting are obtained. Based on the single pick cutting test on natural sandstone, the peak cutting forces obtained by theoretical calculation and physical test are compared, and the main conclusions are drawn as follows:

(1) The number of force chains is inversely proportional to the distribution of force chain length, which is consistent with the morphology of particles under uniaxial compression. The direction of force chain is related to the cutting angle. The average normal force direction is "peanut"-shaped, while the tangential force direction is "petal"-shaped.

(2) The number of force chains increases exponentially with the increase of cutting distance. It is low under small cutting angle and large cutting depth. The length of force chain increases with the increase of cutting distance, and finally stabilizes at 8 particles. The greater the cutting angle, the earlier the force chain formed.

(3) With the increase of cutting angle and the decrease of cutting depth, the normal and tangential cutting forces experience decreasing trends. As inferred in falling fragments, the reduction of cutting angle will shift the tensile failure of rock dominated by compressive stress to shear failure dominated by shear stress.

(4) The theoretical calculation results of peak cutting force for a single pick based on force chain characteristics are close to the test data, and the accuracy is higher than those of the Evans theoretical model and the Li X analytical model.

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