Study on Multi-parameter Coupling and Pre-cut Groove Synergistic Effects in Mechanical Rock Breaking Based on the Discrete Element Method

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Abstract

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Full Text

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Abstract: To address the unclear synergistic mechanism among cutting depth, attack angle, and pre-cut grooves during rock breaking by conical picks, a two-dimensional rock-breaking model was constructed using the discrete-element software MatDEM. A full-factorial design was used to systematically analyze the dynamic characteristics of tool forces, crack-propagation patterns, and the influence of pre-cut grooves during the linear cutting stage. The study finds that, at shallow cutting depths, rock breaking is "tension-dominated" ; when the attack angle is 40°-55°, the average cutting force stabilizes at 80-90 N, corresponding to 550-600 tensile cracks. At deeper cutting depths, the mechanism shifts to "shear-dominated" ; when the attack angle increases to 60°, the average cutting force reaches 150 N, while the number of shear cracks remains at 850–950. Pre-cut grooves promote surface spalling by inducing redistribution of force chains and, at deep cutting depths, strengthen penetrative failure in the "shear-fracture zone." Based on the mesoscopic contact evolution revealed by coordination-number cloud maps, a synergistic criterion of "cutting depth–attack angle–pre-cut groove" is established: for sandstone (medium-hard rock), shallow cutting depths are suitable for attack angles of 40°–50° combined with pre-cut grooves to control damage, while deep cutting depths are recommended to use attack angles of 55°–60° combined with pre-cut grooves to improve efficiency. This provides cross-scale theoretical support for optimizing conical-pick rock-breaking parameters.

Keywords: conical pick; cutting depth; attack angle; pre-cut groove

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Multi-parameter coupling and pre-cut groove synergistic effects in mechanical rock breaking based on the discrete element method

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Abstract: The synergistic mechanism among cutting depth, attack angle and pre-cut groove in conical-pick rock fragmentation remains unclear. Therefore, a two-dimensional linear-cutting model was constructed in the open-source discrete-element code MatDEM and tested through a full-factorial experimental design. Dynamic pick forces, crack-evolution patterns and the mediating effect of a pre-cut groove were quantitatively captured. Results show that at shallow depths ($ $12 mm) fragmentation is tensile-dominated, with the mean cutting force stabilizing at 80 N–90 N for attack angles of 40°–55° and 550–600 tensile cracks generated; at the deep depth (15 mm) the mechanism switches to shear-dominated, the mean force rising to 150 N at 60° while 850–950 shear cracks persist. The pre-cut groove redistributes force chains to pro-

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···promote surface spalling, and under deep cutting, intensifies the penetration of the shear-crushing zone. Coordination maps extracted from temporal coordination-number fields yield a cross-scale criterion: for medium-hard sandstone, shallow cutting benefits from attack angles of 40°–50° combined with a pre-cut groove to control damage, whereas deep cutting favors angles of 55°–60° coupled with a pre-cut groove to enhance efficiency, thus providing a mechanistic basis for parameter optimization in conical-pick rock fragmentation.

Key words: conical pick; cutting depth; attack angle; pre-cut groove

Rock fragmentation is of vital importance in mining and tunnel engineering, and its efficiency, safety, and cost directly determine the success or failure of a project. At present, conventional drilling-and-blasting remains the mainstream rock-breaking technology; however, its shortcomings—such as intermittent operation, low energy utilization, and damage to the surrounding rock—make it increasingly unable to meet the demands of green construction and intelligent mining under the "dual carbon" strategy [1–3]. By contrast, mechanized rock-breaking technologies such as boom-type roadheaders offer advantages including continuous operation, controllable damage, and high safety. Nevertheless, constrained by tool materials, rock properties, and machine power, they are mainly applicable to soft and medium-hard rocks such as coal, bauxite, and phosphate ore. Under hard-rock conditions, mechanized non-blasting rock breaking faces two major challenges: rapid tool wear and low excavation efficiency, which have become key bottlenecks in efficient hard-rock excavation [4].

In response to these issues, researchers have carried out a series of studies, with current efforts focusing mainly on tool-parameter optimization (such as attack angle and pick cone angle), development of new tool materials, and rock-modification technologies [5]. Among these, multi-parameter dynamic coupled optimization of tool parameters (cutting depth–attack angle) and rock modification (pre-cut grooves) is one of the principal strategies for improving the efficiency of mechanized hard-rock mining [6]. In the field of rock-cutting mechanics, the development of theoretical models has been an important driver of research. Early scholars established mechanical systems based on the rigid-contact assumption, forming multiple generations of cutting-force prediction theories founded on the classical Evans model [7]. However, with the accumulation of experimental data and the increasing complexity of actual geological conditions, the limitations of existing theoretical models in predicting cutting forces have gradually become apparent [8]. In particular, comparisons between experimental and theoretical results show that the cutting forces predicted by existing models are generally lower than laboratory measurements, mainly because the influence of attack angle on rock-failure mode has not been fully considered. This has prompted researchers to further explore key factors that may have been overlooked in the models. Although rock-cutting experiments under different working conditions (cutting depth, pick cone angle, and confining pressure) have clarified the interaction mechanism between stress and crack propagation during the dynamic contact process between conical picks and rock, and have established a relatively complete experimental framework for rock-breaking mechanisms [9-11], existing studies have largely focused on the macroscopic mechanical response of conical-pick rock breaking, while lacking analysis of mesoscopic damage evolution. Traditional experimental methods can provide macroscopic cutting-force data, but they cannot comprehensively explain the propagation mechanism of microcracks in rock [12-16]. Among numerical simulation methods, the discrete element method (DEM) has become a key tool for studying rock-breaking mechanisms because it can simulate particle flow and spontaneous crack propagation [17-20]. Existing studies mainly focus on the influence of tool parameters on rock-breaking characteristics.

To improve the rock-breaking efficiency of conical picks, auxiliary measures may be introduced during the rock-breaking process. However, research on the synergy between tool-parameter optimization and rock-weakening measures remains insufficient, and systematic analysis of tool–rock interaction is still lacking [21-22].

In view of this, this study uses the MatDEM discrete-element software to establish a two-dimensional cutting model and investigate the multi-parameter mechanisms of rock breaking by conical picks. The study focuses on analyzing the dynamic responses of cutting depth and attack angle, as well as their synergistic effects with pre-cut grooves, while continuously monitoring cutting force, normal force, crack-propagation direction, and rock-fragment characteristics, thereby providing theoretical support and practical guidance for efficient rock breaking.

1 DEM Principles and Parameter Calibration

1.1 DEM Principles

The core of the discrete element method (DEM) model is to allow a series of particle elements to move in accordance with Newton' s second law of motion, with their motion driven by external loads, forces assigned to particles, or displacement. The force-displacement method is used to update the contact forces generated by the relative motion between particles, while the specific force-displacement laws must be implemented through various contact models [23]. MatDEM can first accumulate discrete elements to construct a rock model with specified physical and mechanical properties, and then simulate crack initiation and propagation as well as stress changes inside the rock. It can analyze, at the microscopic level, the interaction mechanism between conical picks and rock, and can also analyze energy conversion during rock failure. Moreover, the software employs an innovative discrete-element GPU matrix-computing method, giving it a computational efficiency far exceeding that of foreign commercial software [24]. In this study, a linear elastic model is selected as the inter-element contact model. It is the most fundamental and widely applied model in DEM, suitable for describing the basic elastic behavior of materials such as rock. Compared with complex nonlinear models, it has lower computational cost, higher efficiency, and better numerical stability, and is less prone to instability or divergence during simulation.

The initial rock model is constructed according to the particle-flow discrete-element theory. By assigning specific mesoscopic mechanical parameters to the particle system (such as particle stiffness and bond strength), the model is endowed with corresponding macroscopic mechanical properties; the model morphology is shown in Fig. 1(a). In the model, interparticle contact is represented by a breakable bonded model: linear elastic springs are set in the normal and shear directions, respectively. The springs can transmit contact forces and allow a certain amount of deformation; when the contact stress

When the force (normal tensile stress or shear stress) exceeds the bonding-strength threshold, the spring breaks, thereby simulating the initiation and propagation of microcracks inside the rock. The specific connection and mechanical transmission mechanism between particles is shown in Fig. 1(b). This mesoscopic construction method lays the foundation for subsequently simulating the progressive failure of rock during pick cutting—from microcrack evolution to macroscopic fragmentation—and can accurately capture the dynamic mechanical response of "force-crack-breakage."

(a) DEM accumulation model

(b) Particle-unit contact model

Fig. 1 DEM model and contact model between particles

Particle units contact one another through springs and generate interaction forces. The normal spring is used to simulate the normal force (F_n) and normal deformation (X_n) between particle units. The normal force is calculated as follows:

$$F_n = \begin{cases} K_n X_n, & (X_n \leq X_b) \\ 0, & (X_n > X_b) \end{cases} \tag{1}$$

where F_n denotes the normal force; K_n is the normal stiffness; X_n is the normal relative displacement; and X_b is the fracture displacement of the normal spring between two particle units. In the initial state, when the normal relative displacement between adjacent particles satisfies $X_n \leq X_b$, the particles are in a compressed or tensile state; if $X_n > X_b$, the normal spring breaks, tensile force no longer exists between particles, and subsequently only compressive force can be sustained [25].

In addition, the breakable shear spring between particles is used to simulate the shear force (F_s) and shear deformation (X_s). For an intact connection, the shear force is calculated as follows:

$$F_s = K_s X_s \tag{2}$$

where F_s is the shear force; X_s is the relative tangential displacement between particles; and K_s is the tangential stiffness.

The failure criterion of the tangential spring follows the Mohr-Coulomb criterion, expressed as

$$F_{\mathrm{smax}} = F_{\mathrm{s0}} - \mu_p F_n \tag{3}$$

where F_{smax} is the maximum shear force between particles; F_{s0} is the initial shear resistance of a particle unit, i.e., the maximum shear resistance in the absence of an external normal force; and μ_p is the friction coefficient between particle units. Here, F_n denotes the normal force, with pressure taken as negative. Therefore, the greater the normal compressive stress, the greater the maximum shear force between particle units. When the tangential force between units exceeds the maximum shear force, the tangential spring breaks. At this point, relative displacement occurs between particle units, and only sliding friction exists between them, given by

$$F'_{\mathrm{smax}} = -\mu_p F_n \tag{4}$$

where F'_{smax} is the sliding friction force between particle units. The magnitude of the sliding friction force is related only to the friction coefficient between particle units and the normal force; the greater the normal force, the greater the sliding friction force.

In the DEM simulation process, normal and tangential springs are used between particle units to equivalently characterize the mineral cementation inside real rock. Therefore, when the normal spring between particles breaks, this represents the fracture of cementation between minerals inside the real rock; at this time, the tangential spring between particle units in the simulation will also break, and vice versa. That is, the fracture of cementation between minerals in real rock corresponds, in the numerical simulation, to the fracture of both the normal and tangential springs. This indicates that, in the numerical simulation, when the relative displacement between particle units exceeds the smaller value of the normal relative displacement and the tangential relative displacement, the corresponding type of crack will form between particles [26].

1.2 Macroscopic-microscopic conversion and parameter calibration

In this study, MatDEM software was used to construct a uniaxial compression test model and a Brazilian disk splitting model, as shown in Fig. 2.

(a) Uniaxial compression test

(b) Uniaxial compression model

(c) Brazilian disk splitting test

(d) Brazilian disk splitting specimen

Fig. 2 Parameter calibration model

The uniaxial-compression numerical model has dimensions of 100 mm × 50 mm and consists of 5,174 randomly distributed particle elements. The particle-diameter dispersion coefficient is 1.2, with diameters ranging from 0.462 to 0.559 mm and an average diameter of 0.5 mm. The Brazilian-disk numerical model has a diameter of 50 mm and contains 1,972 particle elements. Its particle-diameter dispersion coefficient is consistent with that of the uniaxial-compression model; the particle diameters range from 0.418 to 0.602 mm, and the average diameter is also 0.5 mm.

The physical and mechanical properties of the simulated sandstone are shown in Table 1. The physical and mechanical parameters of sandstone cannot be used directly in the subsequent numerical simulations; therefore, the macroscopic and microscopic parameters of the numerical model must be calibrated [27-29].

Table 1. Physical and mechanical properties of sandstone

E/GPa	σ_c/MPa	σ_t/MPa	$\rho/(\mathrm{g \cdot cm^{-3}})$	$\Phi/(^\circ)$
5.07	52.99 ± 2.08	3.67 ± 0.25	2.36	57.06

In Table 1, E is the elastic modulus, σ_c denotes the compressive strength, σ_t denotes the tensile strength, ρ denotes the density, and Φ denotes the internal friction angle. The Mat-DEM software provides built-in conversion formulas for the macroscopic and microscopic parameters of the discrete-element model [25, 30]. Through these formulas, the macroscopic mechanical properties of the rock can be converted into the mechanical parameters between microscopic particles.

$$K_n = \frac{\sqrt{2}Ed}{4(1-2\nu)} \tag{5}$$

where K_n is the normal stiffness, E is the elastic modulus, d is the particle-element diameter, and ν is Poisson' s ratio.

$$K_s = \frac{\sqrt{2}(1-5\nu)Ed}{4(1+\nu)(1-2\nu)} \tag{6}$$

where K_s is the tangential stiffness.

$$X_b = \frac{3K_n + K_s}{6\sqrt{2}K_n(K_n + K_s)} \cdot T_u \cdot d^2 \tag{7}$$

where X_b is the fracture displacement and T_u is the tensile strength.

$$F_{s0} = \frac{1-\sqrt{2}\mu_p}{6} C_u d^2 \tag{8}$$

where F_{s0} is the initial shear force and C_u is the compressive strength.

$$\mu_p = \frac{-2\sqrt{2} + \sqrt{2}I}{2+2I} \tag{9}$$

where μ_p is the friction coefficient.

$$I = \left[\left(1+\mu_i^2\right)^{1/2} + \mu_i\right]^2 \tag{10}$$

where I is a correlation characterization function of the internal friction angle of the rock, and μ_i is the internal friction coefficient.

After completing the parameter calibration of the uniaxial-compression and Brazilian-splitting models, the corresponding microscopic parameters were obtained by inversion using the macroscopic–microscopic conversion formulas. Table 2 lists the calibrated macroscopic and microscopic mechanical parameters of the rock.

Table 2. Macroscopic and microscopic mechanical parameters

Macroscopic parameter	Value	Microscopic parameter	Value
Elastic modulus E/GPa	5.12	Normal stiffness $K_n/(\mathrm{MN \cdot m^{-1}})$	12.56
Poisson' s ratio ν	0.15	Tangential stiffness $K_s/(\mathrm{MN \cdot m^{-1}})$	4.49

Macroscopic parameter	Value	Microscopic parameter	Value
Tensile strength σ_t/MPa	3.47	Element fracture displacement X_b/m	5.01×10^{-6}
Compressive strength σ_c/MPa	54.28	Initial shear force F_{s0}/N	80.93
Density $\rho/(\mathrm{g} \cdot \mathrm{cm}^{-3})$	2.36	Friction coefficient μ_p	0.38

1.3 Comparison of Test Results and Simulation Results

Comparison between the stress–strain curve from the uniaxial-compression simulation and the test results shows that the error in peak strength is less than 5%, and the failure modes are all axial splitting (Fig. 3). The simulated force–displacement curve of the Brazilian splitting test agrees with the measured values (Fig. 4). After the model validation was completed, the tool–rock contact adopted a linear spring model, with normal stiffness $K_n = 12.56$ MN/m, tangential stiffness $K_s = 4.49$ MN/m, and fracture displacement $X_b = 5.01 \times 10^{-6}$ m.

Fig. 3. Results of uniaxial compression test and simulation results

(a) Uniaxial-compression stress–crack curve.

(b) Uniaxial-compression numerical model and loading.

(c) Cracking in the uniaxial-compression numerical model.

(d) Indoor uniaxial-compression test.

(a) Brazilian splitting displacement–crack curve

(b) Brazilian splitting numerical simulation model and loading

(c) Brazilian splitting numerical simulation cracking condition

(d) Brazilian splitting laboratory test

Fig. 4 Results of the Brazilian splitting test and simulation

2 Construction of the Cutting Model and Model Validation

2.1 Construction of the Cutting Model

The rock specimen model has a height of 300 mm and a length of 150 mm, and is composed of 11 709 discrete particles. The particle-size dispersion coefficient is 0.2, defined as the ratio of the maximum particle diameter to the minimum particle diameter. The model is shown in Fig. 5. A pre-cut groove with a length of 135 mm is formed in the specimen by setting a 15 mm baffle. Since a two-dimensional cutting model is adopted for the numerical simulation in this study, the specific geometric parameters of the pre-cut groove are: length 135 mm and width (depth) 15 mm. The cone angle of the conical pick is 80°, and the tip diameter is 22 mm. The tool is modeled using the Clump cluster method and is regarded as a rigid body. A linear spring model is adopted for the tool–rock contact, with normal stiffness $K_n = 12.56$ MN/m, tangential stiffness $K_s = 4.49$ MN/m, and fracture displacement $X_b = 5.01 \times 10^{-6}$ m. Fig. 5 presents in detail the numerical simulation parameters of the conical pick when the attack angle is γ, indicating the cutting depth, cutting direction, and geometric dimensions.

Fig. 5 Linear cutting model

2.2 Numerical Simulation Scheme

In this study, numerical analysis is carried out using a full-factorial design, with 10 discrete operating conditions set to systematically reveal the mechanism of rock breaking in linear cutting. The cutting depth is set at two levels: 12 and 15 mm. The cutting depths of 12 mm and 15 mm refer to the common cutting-depth range of tunnel boring machine tools. The tool attack angle varies from 40° to 60° in increments of 5°. The linear cutting process is defined as a cutting length of 0.16 m. Continuous cutting simulation is adopted in the numerical model, and the cutting speed of the conical pick is set to 2 m/s, so as to investigate the rock-breaking characteristics of the linear cutting section and the pre-cut groove section (Fig. 6).

Fig. 6 Linear cutting section and pre-cut groove influence section

3 Analysis of the Linear Cutting Process

3.1 Analysis of Changes in Tool Force During the Linear Cutting Process

Fig. 7 shows the variation patterns of the peak cutting force and peak normal force of the conical pick in the linear cutting section with attack angle when the cutting depths are 12 and 15 mm. For the working condition with a cutting depth of 12 mm, the peak cutting force fluctuates with the attack angle, reaching a relative peak at 45°, dropping to a trough at 50°, and then rising again at 60°. The peak normal force as a whole shows a trend of first decreasing slightly and then decreasing significantly, with an obvious trough at 55°, indicating that the attack angle affects the tool force by regulating force distribution and crack propagation. Under the working condition with a cutting depth of 15 mm, the peak cutting force reaches its minimum at 50° and then rises rapidly after 55°. The variation trend of the peak normal force is consistent, with 50° being the main⋯

dominant cutting-force failure mode. Comparison shows that cutting depth changes the mechanism by which the attack angle affects force transmission and rock-failure mode. At the shallow cutting depth of 12 mm, the force response is more complex; at the deep cutting depth of 15 mm, the gradient of force variation with attack angle is more pronounced. This reflects the coupling effect between cutting depth and attack angle, and provides data support for optimizing pick-cutting parameters and balancing energy efficiency with rock-breaking efficiency.

Fig. 7 Variation of peak force of conical pick
(a) 12 mm; (b) 15 mm

By comparing the variation curves of the average tool force in the linear cutting stage at cutting depths of 12 and 15 mm, Fig. 8 reveals the mechanism by which cutting depth affects the dynamic characteristics of average cutting force and average normal force. At a cutting depth of 12 mm, the average cutting force remains relatively stable at 80–90 N over the attack-angle range of 40°–55°, and jumps to 110 N at 60°. This is because, at small angles, rock fragmentation is dominated by "tensile failure," whereas at large angles it shifts toward shear-dominated fragmentation. The average normal force decreases continuously as the attack angle increases, dropping from 120 N at 40° to 80 N at 60°, reflecting how the attack angle regulates the proportion of the "normal tensile–cutting shear" force components. Under the cutting-depth condition of 15 mm, the average cutting force gradually increases with attack angle, showing a monotonic rising trend from 90 N to 150 N. This is because, under deep cutting, rock fragmentation is "shear-dominated," and an increase in attack angle strengthens the transmission of cutting force. The average normal force exhibits a "V-shaped" distribution, decreasing to 50 N at 50° and rising again at 40° and 60°, indicating the effects of reliance on normal tension at small angles and cutting-force compression at large angles. Thus, cutting depth significantly changes the dominant mode of tool force: shallow cutting depth corresponds to a "tension-shear transition," while deep cutting depth corresponds to "shear dominance." Under different cutting depths, the attack angle respectively balances normal tension and enhances cutting-shear efficiency, providing a basis for optimizing pick-cutting parameters.

Fig. 8 Variation of average force of conical pick
(a) 12 mm; (b) 15 mm

3.2 Crack propagation during the linear cutting process

Figure 9 shows the crack propagation inside the rock under cutting depths of 12 and 15 mm. From the figure below, it can be seen that cutting depth significantly affects the crack-evolution pattern. For a cutting depth of 12 mm, the number of tensile cracks as a whole follows a "fluctuation-stabilization" trend. When the attack angle is 40°–45°, the number of cracks decreases slightly and then remains at 550–600, indicating that, during cutting at low attack angles, the tensile failure induced by the tool is relatively stable. The number of shear cracks shows a "V-shaped" fluctuation, falling to 600 at an attack angle of 50°, which indicates that shear fragmentation and tensile fragmentation are optimally coordinated at this angle. At 40° and 60°, the number of shear cracks rises again to more than 700, showing that when the attack angle is too small or too large, shear-force-dominated fragmentation promotes the propagation of shear cracks. Under the cutting-depth condition of 15 mm, the number of tensile cracks varies with attack angle in a "double-hump" pattern, reaching a peak of 717 at an attack angle of 55°. This indicates that, under deep cutting, the attack angle affects the initiation efficiency of tensile cracks by regulating the concentration of cutting force, and 55° is the angle at which tensile cracks are most likely to develop. At an attack angle of 55°, the number of shear cracks shows "high-level fluctuation," lying within the range of 850–950, significantly higher than at the 12 mm cutting depth. This indicates that, under deeper cutting, rock fragmentation is shear-dominated; shear cracks are the main fracture form, and the influence of attack angle on their number is relatively mild, with only a slight decrease at 50° due to the crack-synergy effect. Comparison shows that cutting depth changes the dominant crack mode: under shallow cutting, tensile and shear cracks evolve competitively, and the attack angle regulates crack number by balancing the force components; under deep cutting, shear cracks dominate, the number of tensile cracks depends on the "stress-concentration efficiency" of the attack angle, and the overall number of cracks increases significantly as cutting depth increases.

Fig. 9 Expansion of cracks inside the rock
(a) 12 mm; (b) 15 mm

Figure 10 presents the distribution of crack propagation inside the rock under different working conditions. By comparing rose diagrams of crack propagation at cutting depths of 12 and 15 mm, the influence of attack angle on the evolution of tensile and shear cracks during rock breaking by the conical pick is analyzed, together with the rock-fragmentation characteristics at different cutting depths. At a cutting depth of 12 mm, tensile cracks (red) account for a significantly higher proportion than shear cracks (blue) and are concentrated in the range of 105°–165°. As the attack angle changes, under small attack angles (40°–50°), tensile cracks are densely distributed in the range of 120°–150°, reflecting a tensile-failure mode dominated by normal stress. Under large attack angles (55°–60°), tensile cracks shift toward the range of 105°–135°, and the proportion of shear cracks increases slightly, indicating that cutting force gradually dominates the failure process. At this cutting depth, the crack distribution is strongly discrete, showing a pattern dominated by shear failure, with tensile as

an auxiliary mixed mode, and the stress field exhibits a dynamic transition between the "normal" and "cutting" directions as the attack angle is adjusted. When the cutting depth increases to 15 mm, the proportion of shear cracks (blue) rises significantly, forming a "dual-dominant" distribution together with tensile cracks, and the overall distribution converges toward the $0° \sim 90°$ interval. At small attack angles ($40° \sim 50°$), shear cracks are concentrated in the $45° \sim 75°$ interval, while tensile cracks still dominate the $105° \sim 150°$ interval, indicating that under a large cutting depth the normal stress and cutting force act synergistically, and the rock simultaneously undergoes "shear slip–tensile spalling." At large attack angles ($55° \sim 60°$), the proportion of shear cracks further increases, the dominant direction stabilizes at $30° \sim 60°$, and the distribution range of tensile cracks narrows, reflecting a cutting-force-dominated shear failure mode. Under this cutting depth, the convergence of crack directions is enhanced, and the contribution of shear failure increases. Comparing the rose diagrams at different cutting depths, the cutting depth presents a "tensile–shear" transition mechanism: at shallow cutting depths, rock failure is dominated by tensile cracks with dispersed directions, reflecting a normal-stress-dominated "surface spalling" mode, in which energy is dissipated through the development of multidirectional microcracks; at large cutting depths, the proportion of shear cracks jumps to a level comparable to that of tensile cracks, and the directions converge toward the cutting direction, reflecting a cutting-force-dominated "deep shear" mode, in which energy is concentrated to drive rock fragmentation along the motion direction of the pick. The attack angle amplifies the cutting-depth effect by regulating the distribution ratio between normal force and cutting force: small attack angles strengthen normal tensile action, whereas large attack angles promote cutting-induced shear action. Ultimately, this is manifested as the coordinated variation of the directional dispersion of the crack rose diagrams and the shear-crack proportion with cutting depth and attack angle.

Fig. 10 Distribution of crack extension within the rock under different working conditions

Subfigures:
(a) 12 mm-40°; (b) 12 mm-45°; (c) 12 mm-50°; (d) 12 mm-55°; (e) 12 mm-60°; (f) 15 mm-40°; (g) 15 mm-45°; (h) 15 mm-50°; (i) 15 mm-55°; (j) 15 mm-60°.

Legend: red—tensile cracks; blue—shear cracks. Axis label: number of cracks.

3.3 Analysis of the Influence of Pre-cut Grooves

Figure 11 shows the coordination-number cloud maps for cutting depths of 12 mm and 15 mm and attack angles of 40°-60°. From the mesoscale particle-contact dimension, it reveals the differences in the rock-breaking mechanism produced by the synergistic effect of the pre-cut groove and the attack angle. In the coordination-number color bands, warm colors indicate high contact and structural integrity, whereas cool colors indicate low contact and damage development. At a cutting depth of 12 mm, regulation by the attack angle drives the pre-cut groove in the force-chain direction to induce "tension-dominated" contact failure. When the pick attack angle is 40°, the normal force dominates the tensile cracks inside the rock, which propagate along the groove body–pick line and peel off, showing the characteristic of "surface spalling" at shallow cutting depth. When the pick attack angle is 50°, the pre-cut groove guides cracks to penetrate progressively; at 60°, the cutting-force component is enhanced, forming a "cutting band" and reflecting cutting-force-dominated "shear slip." After the cutting depth increases to 15 mm, attack-angle regulation exhibits a "cutting-dominated" mode. At 40°, cool-colored zones on the rock surface are more concentrated; the normal force triggers "deep tensile fissures," and fragmentation extends toward the deeper layer. The failure range is greater than that at a cutting depth of 12 mm, showing "penetrative failure." At 50°, "progressive failure" is strengthened, and continuous channels with coordination numbers of 3–4 form between the spalled rock mass and the pick, producing an enhanced force-chain transmission effect and a significant increase in fragmentation volume, which reflects the synergistic enhancement effect of cutting depth and attack angle. At 60°, the width of the cutting band increases, and the pre-cut groove cooperatively forms a "cutting fragmentation zone," making the pre-cut-groove effect more pronounced. Comparison in Fig. 11 shows that changes in cutting depth alter the force conditions on the pick and the depth of force-chain transmission. At shallow cutting depth, contact failure is discrete tensile failure; fragmentation is shallow, and energy is dissipated in microcracks. At large cutting depth, the process shifts toward directional cutting; fragmentation is deeper and more efficient, with energy driving deep fragmentation. The attack angle amplifies tensile failure at shallow cutting depth and strengthens the cutting effect at large cutting depth.

Fig. 11 Coordination-number conditions of units during the cutting process
Fig. 11 Number of unit allocations in the cutting process

4 Conclusions

Based on a discrete-element simulation of sandstone, this study used MatDEM to establish a two-dimensional numerical model, simulated the linear cutting process of a pick-shaped cutter under different cutting parameters, and systematically investigated the synergistic influence of attack angle, cutting depth, and pre-cut groove on rock-breaking characteristics. The main conclusions are as follows.

1) Cutting depth governs the transition of the rock-breaking mode: at shallow cutting depths ($ 12*mm*), *normalforcedominatestensilefailure*, *cracksaredistributeddiscretely*, *and* mm), cutting force dominates shear failure; the number of shear cracks increases by 50% compared with shallow cutting depth, forming a directional "cutting fragmentation zone," and the average cutting force

increases linearly with increasing attack angle.

2) Attack angle regulates the force–crack coupling efficiency: at shallow cutting depth, an attack angle of 50° balances the “normal-tension and cutting-shear” components, minimizing the fluctuation of the average force and optimizing the crack-synergy effect. At large cutting depth, an attack angle of 60° strengthens cutting-force transmission. The pre-cut groove reduces the crack-initiation threshold, expanding the regulatory range of the attack angle on tensile cracks under shallow cutting depth.

3) In engineering applications, at shallow cutting depth ($ 12*mm*), *theattackanglemaybeoptimizedto*45°–55°
crackdirectionandreducesurrounding—rockdamage, *whichissuitableforfinetrimmingoftunnelprofile*
mm), increasing the attack angle to 55°-60° can make use of the convergence of shear cracks to improve hard-rock fragmentation efficiency and is suitable for efficient drivage of mining faces. This provides a microscopic basis for optimizing pick parameters, and helps realize on-demand switching between “tensile spalling” and “cutting fragmentation,” as well as matching tool design with construction parameters.

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Note: Figure translations are in progress. See original paper for figures.