Rock Breaking Mechanism Analysis and Structure Design of the Conical PDC Cutter Based on Finite Element Method

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ABSTRACT - In order to explore the rock breaking mechanism of the conical Polycrystalline Diamond Compact (PDC) cutter, and better design the cutter's structure, a finite element model is proposed. Simulation results show that: the conical PDC cutter breaks rock in a tensile and shear way; in the structure design of the conical PDC cutter, the optimized conical apex angle should be below 80°, and the smaller the vertex radius, the easier it is for the cutter to eat into the rock; the back rack angle has a great influence on the rock breaking performance of the conical PDC cutter, and the best back rake angle should be between 10° to 15°. According to the design results, a new PDC bit with conical PDC cutters is designed. Field test results of the new bit show that, the bit drilling life in hard rock formation can be significantly improved, and the drilling cost can be reduced remarkably.

Index Terms - Conical PDC Cutter, Finite Element Method, Rock Breaking Mechanism, Structure Design

I INTRODUCTION

With the development of drilling technology in oil and coal drilling engineering, the formation situation is increasingly complex. High degree of hardness and abrasivity rocks, such as quartz sandstone, conglomerate and taconite, are often encountered [1]-[2]. When drilling in these rocks, cutter breakage, delamination and serious abrasion are often occurred, which lead to the reduction of bit service life, and unable to meet the requirements of drilling construction [3].

In order to improve the bit performance, experts have done some researches on the rock breaking mechanics of bit, so that it can provide guidance for the design of PDC drill bit [4]-[7]. But all the researches are based on cylindrical PDC cutter, which breaks rock in a shear way.

Now a new "shear-plough" rock breaking mode is proposed, and a new PDC bit is designed by utilizing conical PDC cutters. The conical PDC cutter was proposed by America Novatek International Company first, they stated that the cutter's impact and abrasive resistance were significantly higher than that of cylindrical PDC cutter [8]. Smith Company invented a new PDC bit by placing Stinger conical PDC cutter at the center of bit, which can minimize bit lateral vibration, and increase local rock crushing stress [9]-[10]. Soon afterwards, Smith Company introduced a new PDC bit by placing Stinger conical PDC cutters on the bit's blade, so that the drilling load can easily be concentrated, and the control of tool surface was better [11]-[12]. Therefore, it can be known that, the attack and impact resistance abilities of PDC bit with conical PDC cutter can be greatly improved. But the research on the rock breaking mechanism of conical PDC cutter is barely reported, and the study on the structure design of conical PDC cutter, which has large impact on its rock breaking performance, is relatively less. So the rock breaking mechanism and structure optimal design of conical PDC cutter are carried out in this paper, which will provide a basis for the optimal design of "shear-plough" PDC bit.

II FINITE ELEMENT MODEL OF ROCK BREAKING PROBLEM

In recent years, finite element method has been widely used in the study of rock breaking problems, which can simulate the influence of material heterogeneity, non-linear and boundary condition on cutting process. Tulu I B developed 3D numerical single cutter model to analyse the relation between cut load, cut angle and cut depth. The cutter was consisted of PDC disc and tungsten carbide backing, the strain-softening Mohr-Coulomb plasticity model was used to define the failure of rock, a "soft" contact was used to define the contact between rock and cutter [13]. Jaime M C modeled

This work was supported in part by the National Natural Science Foundation of China (No. 51774320)
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the problem of rock cutting by an advancing drilling cutter, he found out that the Lagrange approach had no element diffusion problem as that of Euler and Arbitrary Lagrangian Eulerian approaches, the fragmentation progression obtained from Finite Element method could capture various fracture phases well from crack initiation, to debris generation [14]. Ju P designed the crown shape of PDC bit using Ls-Dyna method, in which the rock material was simulated by plastic kinematic hardening model, and the erosion contact type was defined between blade and rock, the Any Lagrangian-Eulerian algorithm was adopted [15]. Pryhorovska T O simulated the rock linear and circular cutting processes for different shapes of PDC drill bit cutters, the Johnson-Cook criterion of accumulated plastic deformation was selected as the failure criterion of rock, BoronCarbi and Concrele L material types were selected for cutting tools and rock slab simulation respectively [16].

With the gradual deepening of research, the finite element method of rock breaking problem is mature, and can be used to study the dynamic interaction between bit, rock and cuttings, also the simulation results are in good agreement with experimental results [17]-[18]. Therefore, in the absence of experimental data, finite element method can be used to study the characteristics of the rock breaking process of bit and cutters. Furthermore, the rock breaking process is very complicated, there is no explicit analytic solutions, so the finite element method is a good and practical tool for the study of rock breaking problems.

A. Geometry Model

To simplify the calculation, some assumptions are made:

(1) Ignoring the influence of confining pressure, temperature and drilling fluid.

(2) Ignoring the wear of the cutter.

(3) The cutter eats into the rock in the form of a spiral. Since the spiral angle is small, the spiral movement form can be simplified as a linear cutting.

Thus, a model is established to represent the 3D geometry of linear cutting (shown as Fig 1). Solid 164 3D element is adopted. The size of the conical PDC cutter is Φ13.44×15mm, and the size of rock is 120mm×80mm×30mm. The rock specimen is generated on rectangular grids while the cutter is generated as mixed rectangular and triangle grids. The grid size is as small as possible to improve the calculation accuracy.

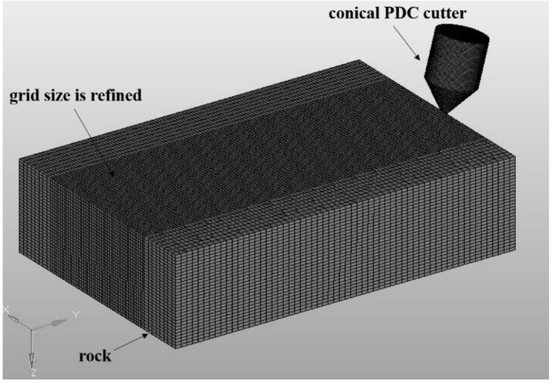


Fig 1. 3D geometry model rock breaking by conical PDC cutter

B. Material Model

The rock behaviour is predominantly inelastic, in order to represent the deformation characteristics of rock, elastic plastic with kinematic hardening theory is chosen for the basis of rock material.

For the mixed hardening, the yield condition is:

$$\varphi = 1.5(S_{ij}^{n+1} - \alpha_{ij}^{n})(S_{ij}^{n+1} - \alpha_{ij}^{n}) - \sigma_{y}^{2n} = 0 \qquad (1)$$

Where: s_{ij}^{n+1} represents the trail elastic deviatoric stress state at time t_{n+1}; α_{ij}^{n} is the co-rotation rate at time t_n; σ_y^n is the yield limit at time t_n.

Considering the effect of strain rate on material properties, Cowper and Symonds model is adopted, and the yield strength at time t_n can be expressed:

$$\sigma_y^n = (1 + \frac{\dot{\varepsilon}}{C})(\sigma_0 + \beta E_P \varepsilon_{eff}^n) \qquad (2)$$

Where C and β are user defined input constants, σ_0 is the initial yield strength, E_P is the plastic hardening modulus, ε_{eff}^n is the effective plastic strain at time t_n, $\dot{\varepsilon}$ is the strain rate.

$$E_P = \frac{E_t E}{(E - E_t)} \qquad (3)$$

$$\varepsilon_{eff}^n = \int_0^t (\frac{2}{3} \dot{\varepsilon}_{ij}^n \dot{\varepsilon}_{ij}^n)^{0.5} dt \qquad (4)$$

$$\dot{\varepsilon} = \sqrt{\dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij}} \qquad (5)$$

Where E is the elastic modulus, E_t is the tangential hardening modulus, $\dot{\varepsilon}_{ij}$ is the total strain rate, and $\dot{\varepsilon}_{ij}^n$ is the plastic strain rate at time t_n.

So, the stress tensor at time t_{n+1} can be expressed:

$$\sigma_{ij}^{n+1} = S_{ij}^{n+1} + (p^{n+1} + q)\delta_{ij} \qquad (6)$$

The pressure p^{n+1} can be obtained:

$$p^{n+1} = -k \ln(\frac{V^{n+1}}{V_0}) \qquad (7)$$

Where k is the bulk modulus, V_0 and V^{n+1} are the element volume at initial time and time t_{n+1} respectively, q is the artificial volume viscous damping.

Since the damage mechanism of rock is related to the plastic deformation, the fully damaged state of rock is determined by plastic strain value. The judge criterion can be expressed:

$$\varepsilon_{eff}^{p} \le \bar{\varepsilon}_{eff}^{pl} \tag{8}$$

Where $\bar{\varepsilon}_{eff}^{pl}$ is the effective plastic strain of the rock been totally damaged.

The cutting material of cutter is polycrystalline diamond layer, its hardness and strength are far greater than rock, so the cutter can be properly and accurately treated as rigid material, also the rigid material type is very cost efficient.

Table I shows the material parameters of cutter and rock. The granite is chosen because of its high hardness and strength.

Table I

MATERIAL PARAMETERS OF CUTTER AND GRANITE

	Density Kg/m^3	Elasticity Modulus GPa	Poisson ratio	Compressive Strength MPa	Shear Strength MPa	Tensile strength MPa
cutter	3560	850	0.07			
granite	2800	62	0.26	166	19.8	10

C. Boundary Conditions and Load Applying

The cutter moves toward the rock while the rock remains stationary, so all the node degrees of freedom of the rock on the boundary surface are fixed. A constant velocity of 0.5m/s is applied to the cutter specimen in the global Y direction, the cutting depth is set as 2mm.

The contact friction between cutter and rock is based on Coulomb's formula, and the frictional energy is included in sliding interface energy. In order to show the degradation of rock mechanical properties (strength and stiffness) when external loading is applied on the rock, two-way treatment of eroding contact is chosen, and penalty contact algorithm is adopted, the contact stiffness is calculated using soft constraint-based approach.

In order to avoid the effect of boundary wave reflection, non-reflecting boundary condition is applied on the rock boundary surface. The Flanagan-Belytschko hourglass viscous damping algorithm is used to control the hourglass caused by large deformation.

The cutting process involves large deformation, so in order to overcome the computational difficulties caused by grid distortion, Arbitrary Lagrangian Eulerian method is adopted. In this method, the motion of the grid is independent of the material, which can minimize the distortion of the grid, and improve calculation accuracy.

III RESULTS AND DISCUSSION

A. Stress Distribution and Force Variation

Fig 2 shows the Von Mises stress state and the force curve of cutter. The conical PDC cutter ploughs a strip groove on the rock surface. At the front of the cutting edge, there exists stress concentration points.

In the simulation, the forces fluctuate dramatically over time. The main reason is that, when the rock element is eroded, there is a loss contact between the rock and cutter, and the forces drop suddenly as the rock element in front of the cutter is chipped away. After that, the cutter eats into other rock elements, the forces increase rapidly.

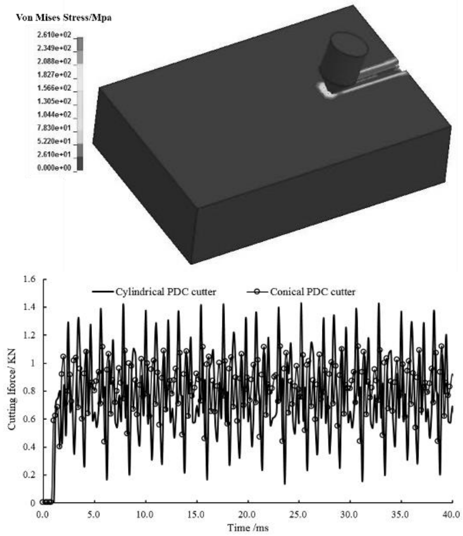


Fig 2. Stress state and force variation of conical PDC cutter

Fig 3 shows the Von Mises stress distribution diagrams of cylindrical and conical PDC cutters. The back rake angles of the cylindrical and conical PDC cutters are -15° and 15° respectively. For the cylindrical PDC cutter, the influence area on the rock is mainly located at the front of cutter, and the maximum stress on the rock appears at the front of cutting edge. With the movement of cutter, the fractures inside the rock propagate approximately horizontal along the cutting direction, and gradually extends to the rock free surface, which reflects the shear rock breaking mechanism of cylindrical PDC cutter.

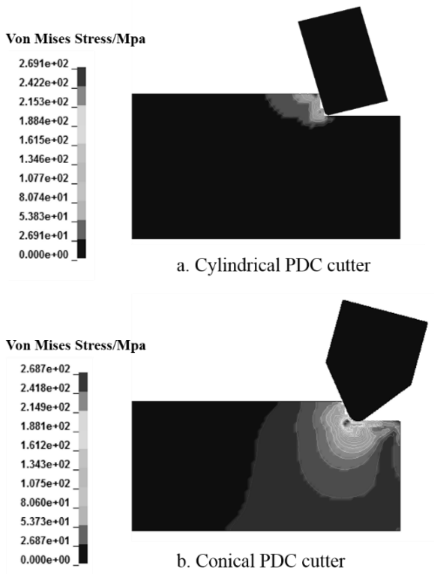


Fig 3. Rock Von Mises states with cylindrical and conical PDC cutters

While for the conical PDC cutter, the maximum Von Mises stress of rock appears under the vertex of conical PDC cutter, where the rock is squeezed, and stress concentration is formed. The influence area on the rock propagates outward along the vertex of cutter, micro-fractures occur inside the rock, and with the movement of cutter, the fracture gradually extends to the free surface of rock, which reflects the tensile-shear rock breaking mechanism of conical PDC cutter.

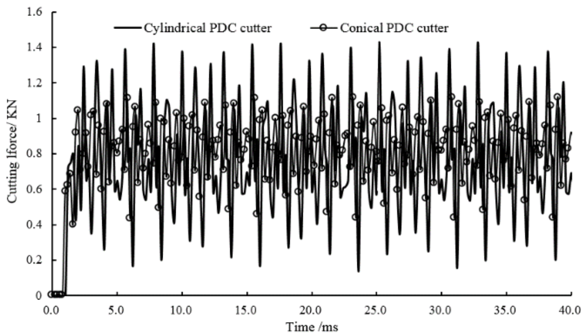


Fig 4. Cutting force with time

Fig 4 shows the cutting force curves of conical and cylindrical PDC cutters with time. The fluctuation range of the cutting force of conical PDC cutter is less than that of cylindrical PDC cutter. This is because the conical PDC cutter ploughs the rock in a way of point contact, the imbalance force is much smaller, and the working state is more stable. The average cutting forces of conical and cylindrical PDC cutters are 827.1N and 811.3N respectively, the cutting force needed by cylindrical PDC cutter is slightly smaller than that of conical PDC cutter.

B. Structure Optimization Design of Conical PDC Cutter

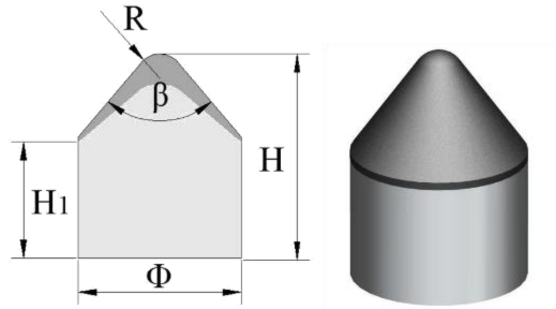


Fig 5. Structure parameters of conical PDC cutter

The main structure parameters of conical PDC cutter are the diameter Φ, the total height H, the hard alloy height H1, the cone apex angle β, and the cone vertex radius R (shown as Fig 5). The cone apex angle β and cone vertex radius R have big impact on the force and wear of cutter, so the focal point of the conical PDC cutter's structure design are apex angle β and cone vertex radius R.

Keeping the diameter 13.44mm, the hard alloy height 10mm, the vertex radius 2mm, the back rake angle 15°, and the cutting depth 2mm unchanged, the influence of conical apex angle on cutter force is analysed. The conical apex angle is set as 70°, 72°, 75°, 80°, 82° and 85° respectively. Fig 6 shows the simulation results of cutter force with different conical apex angle.

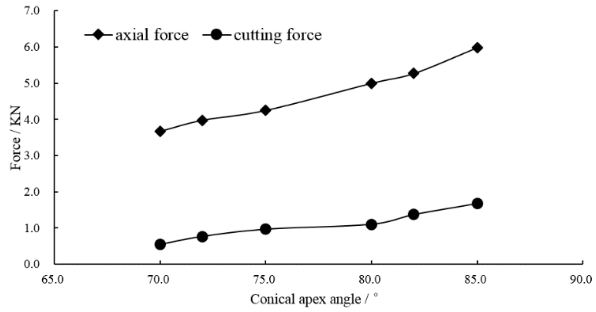


Fig 6. Cutter force with different conical apex angle

As shown in Fig 6, the axial force and cutting force of conical PDC cutter increase gradually as the conical apex angle increases, and when the conical apex angle is greater than 80°, the increasing trend becomes steeper. It can be explained that, with the increasing of conical apex angle, it becomes more and more difficult for the cutter to eat into the rock, and the transverse and longitudinal vibrations of the cutter is getting stronger. Therefore, the optimized conical apex angle should be smaller than 80°. Meanwhile in order to ensure the strength of cutter, the conical apex angle should not be too small.

Keeping the diameter 13.44mm, the hard alloy height 10mm, the conical apex angle 80°, the back rake angle 15°, and the cutting depth 2mm unchanged, the influence of vertex radius on cutter force is analysed. The vertex radius is set as 1mm, 1.25mm, 1.5mm, 1.75mm and 2mm respectively. Fig 7 is the simulation results of cutter force with different vertex angle.

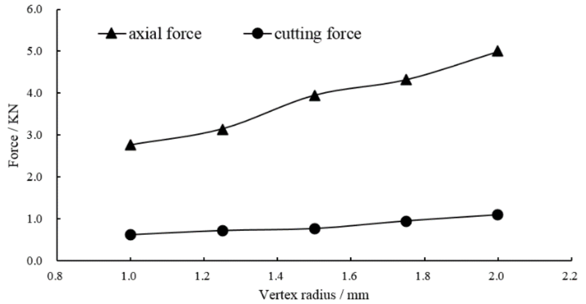


Fig 7. Cutter force with different vertex angle

Fig 7 shows that, the force of conical PDC cutter increases linearly with the increase of cone vertex radius. It means that, the smaller the vertex radius, the easier it is for the cutter to eat into the rock. But as the decrease of vertex radius, the conical tip of the cutter is easier to crack, so the vertex radius should not be too small.

C. Back Rake Angle Design of Conical PDC Cutter

The back rack angle is mainly related to the stress state of rock, and it has great influence on rock breaking performance. For the conical PDC cutter, in order to make good use of its tensile-shear rock breaking ability, the value of the back rake angle should be set to positive (shown as Fig 3). Setting the diameter 13.44mm, the hard alloy height 10mm, the vertex radius 2mm, the conical apex angle 80°, and the cutting depth 2mm unchanged, Fig 8 shows the simulation results of cutter force with different back rake angle.

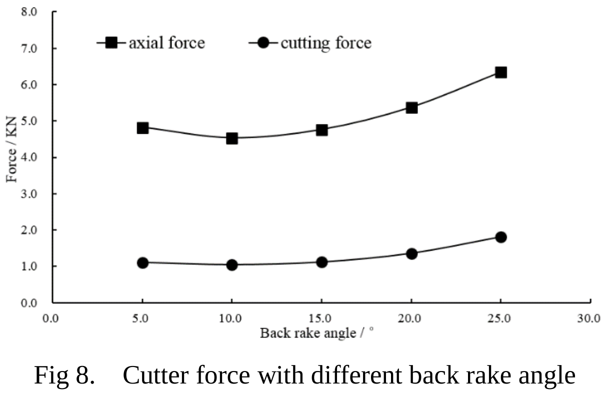


Fig 8. Cutter force with different back rake angle

As shown in Fig 8, the axial and cutting forces show an approximate parabola trend with back rake angle. When the back rake angle is over 15°, the axial and cutting forces increase obviously. Therefore, for the best drilling performance, the optimal back rake angle of conical PDC cutter should be between 10° and 15°.

IV FIELD TEST

According to the optimization design results shown in section III, a new PDC bit with conical PDC cutters is designed. The diameter of the new bit is 94mm, and the crown profile is “line-arc” shape. The main cutting parts of the bit are conical PDC cutters, and the total number of which is 12. The gauge cutters are cylindrical PDC cutters, and the total number of which is 4. The diameter of conical PDC cutter is 13.44mm. The cone apex angle and cone vertex radius are 80° and 1.5mm respectively. The back rake angle of conical PDC cutters is set between 10° and 15°. Fig 9 is the photo of this new PDC bit.

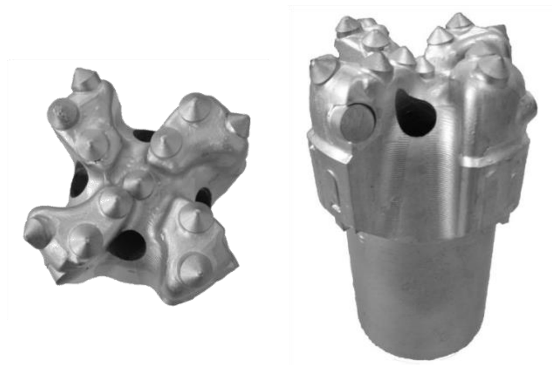
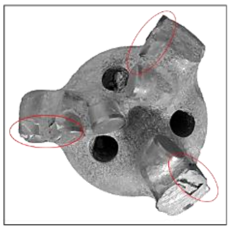


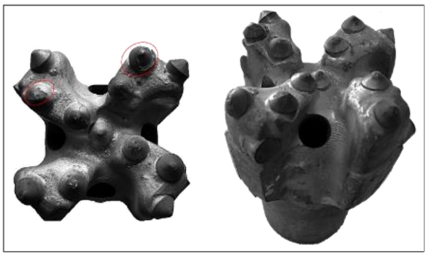
Fig 9. The photo of new PDC bit

Field test was carried out at Yian coalmine, the drilling purpose was to draw off water, ZDY3200S drilling rig and Φ73mm flat drill pipe were used. The drilled rocks were mainly limestone and siliceous cemented sandstone, and the solid coefficient of which were more than 9. The cumulative used number of Φ94mm new PDC bit was 3, the accumulated drill footage of these three bits were 15m, 13m and 10m, and the drilling efficiency of them were 2.5m/h, 2.3m/h and 2.0m/h. While for the arc PDC bits used before, the average drill footage and drilling efficiency were 5m and 2.5m/h respectively. Fig 10 shows the photos of the bits after used.

The average drilling efficiency of the new PDC bit was 2.26m/h, which was a little lower than that of arc PDC bit. While the average drilling footage of the new PDC bit was 12.67m, which was much higher than that of arc PDC bit. As shown in Fig 10, the wear of arc PDC bit was more serious, its cutters were easily to be chipped away. For the new PDC bit, only a few cutters were broken from the cone tip, the life of the new PDC bit was longer than that of arc PDC bit. Field tests show that, when drilling in hard rock, the bit life can be improved drastically with the new designed PDC bit, and the drilling cost can be saved significantly.



Used arc PDC bit photo



Used new PDC bit photo

Fig 10. Used PDC bits photos

V CONCLUSION

(1) It is beneficial to enhance bit attack and impact resistance abilities for hard rock drilling by designing PDC bit with conical PDC cutters. But there is little theoretical research on the conical PDC cutter. Therefore, a finite element method is proposed, the study of the rock breaking mechanism and the structure design of conical PDC cutter are carried out, which can provide the basis for the best design of "shear-plough" PDC bit.

(2) Simulation results show that, the conical PDC cutter breaks rock in a tensile and shear way; the optimized conical apex angle should be smaller than 80°; and the smaller the vertex radius, the easier it is for the cutter to eat into the rock; also the best back rake angle should be between 10° and 15°.

(3) Field tests show that, for the new designed PDC bit with conical PDC cutters, although the drilling efficiency was a little lower than that of the arc PDC bit, the bit life can be improved drastically when drilling in hard rock, and eventually the drilling cost can be saved significantly.

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