The Mechanical Model and the Mechanism of Rock Breaking of Ridge Cutter

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Abstract

The ridge cutter is a new type of rock breaking method, however, there has few studies on its theories at home and abroad .The geometrical equation of the ridge cutter is obtained by establishing the coordinate system of the ridge cutter and the mechanical analysis of the cutting process is carried out. The cutting mechanics model of the ridge cutter is established, All that prepared for the design theory of PDC bit or the ridge cutter. Based on the Drucker-Prager criterion and the failure criterion of the equivalent plastic strain, a finite element analysis model of ridge cutter intrusion and cutting rock based on ABAQUS was established. Through the numerical simulation and theoretical analyses, two mechanisms will be explored, which include the mechanism of rock failure in the process of ridge cutter intrusion and the mechanism mainly composed of tensile fracture and shear failure. The results provide the basis for the numerical simulation calculation and design of the ridge cutter PDC bit.

Keywords

Cutter,mechanical model,geometrical equation, mechanism of rock breaking ,numerical simulation

1. Introduction

The ridge cutter is the new PDC cutting cutter from the Smith launched AxeBlade bit, which has a unique cutter profile. In the practical application, compared to the ordinary PDC bit, AxBlade PDC bit has a higher stability [1], can reduce 20% torque, while increase 27% drilling speed .These excellent properties owe to the unique cutter surface structure of the cutter, so it is urgent to seek into research on the basic theory of the ridge cutter and the mechanism of rock crushing. Through the establishment of the coordinate system, the geometrical equation of the ridge cutter in the coordinate system is obtained, and the force analysis of the cutter cutting process is carried out to obtain the mechanical model of the ridge cutter. The finite element software ABAQUS is used to simulate the process of the ridge cutter broken rock, analyze the stress change and the crushing effect of the rock. Combining the theoretical research and experience, the mechanism of the rock fracture of the ridge cutter during the invasion and cutting process is analyzed.

2. Cutting Geometric Equation and Stress Model of Ridge

The geometrical equation of the ridge cutter mainly includes the characteristic line of the cutter, the surface equation, which is one part of the basic theory of the geometrical geometry of the PDC bit, and the basis of the numerical calculation of the cutting section of the cutting cutter.The analysis of the forced state of a cutter cutting process of rock ridges is an indispensable part of its mechanical model, rock breaking mechanism and design theory research. In this paper, the geometrical equation and mechanical model of the ridge cutter are established in the unified coordinate system, which paves the way for the design of the PDC bit.

2.1 Geometric equation of the ridge cutter

The baseline coordinate system [2] is based on the cutting cutter of rock cutting. The origin of the coordinate system is at the center of the cutting cutter (the midpoint of the central ridge of the ridge), the OZ axis over the cutter center, is perpendicular to crown profile curve of the drill; the OY axis points to the circumferential velocity direction of the O point; the OX axis points to the center axis of the drill bit.

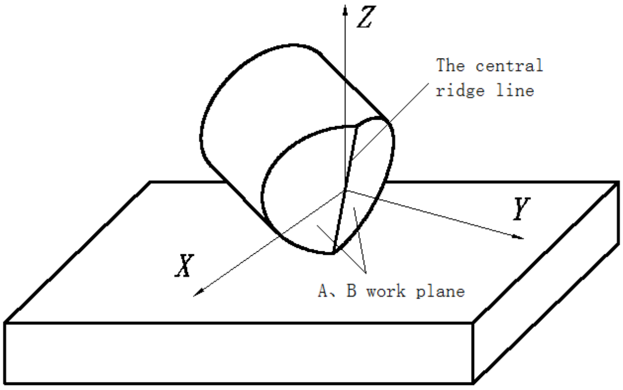


Fig1. Baseline coordinate system

Without considering the side rake angle of the cutting cutter, the cutting speed direction of the cutter center point and its central axis are always in the YOZ plane. In order to facilitate the distinction between the cutting faces, the face of the X-axis positive plane is A, X-axis negative is B work plane. A, B face line is regarded as the center of the ridge line (Usually, the cutter ridge is the central ridge line), and the cutter cylindrical surface line for the cutter edge ridge.

The angle between the cutter ridge of the cutter center and the plane of the cutter and the plane of the YOZ where the centerline lies is called the cutter spiral angle of the cutting cutter of the ridge cutter. According to the right-handed screw rule, the counterclockwise is positive and clockwise is negative The plane equation of the cutter.

$$x\cos\theta - z\sin\theta = 0 \tag{1}$$

The cutter caster angle is α and the plane equation of the ridge line at different cutter spiral angle is:

$$y\cos\alpha - z\sin\alpha = 0 \tag{2}$$

So the equation of the cutter ridge line in the coordinate system is:

$$\begin{cases} x\cos\theta - z\sin\theta = 0 \\ y\cos\alpha - z\sin\alpha = 0 \end{cases} \tag{3}$$

In the vertical plane of the center of the cutter ridge, the angle of the two working plane is φ（φ＜π）cutter face angle and the cutter spiral angle is θ, and the plane equation of the plane of work can be obtained by coordinate transformation:

$$x\cos\theta\cos\frac{\varphi}{2} + y\left(\sin\alpha\sin\theta\cos\frac{\varphi}{2} - \cos\alpha\sin\frac{\varphi}{2}\right) - z\left(\sin\theta\cos\alpha\cos\frac{\varphi}{2} + \sin\alpha\sin\frac{\varphi}{2}\right) = 0 \tag{4}$$

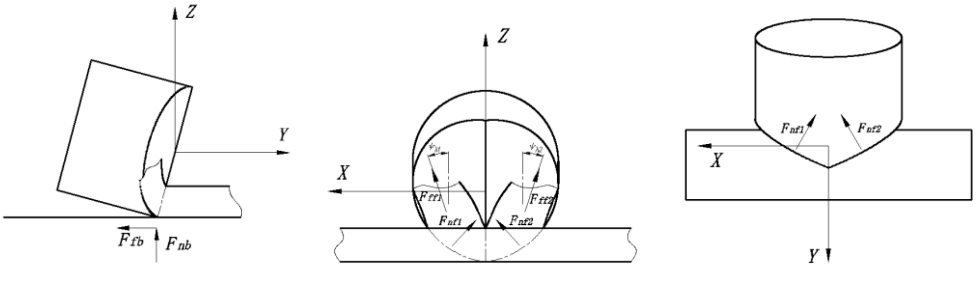
At the same time, we can get the cutter edge ridge equation:

$$\begin{cases} x^2 + (y\sin\alpha - z\cos\alpha)^2 = R^2 \\ x\cos\theta\cos\frac{\varphi}{2} + y(\sin\alpha\sin\theta\cos\frac{\varphi}{2} - \cos\alpha\sin\frac{\varphi}{2}) - z(\sin\theta\cos\alpha\cos\frac{\varphi}{2} + \sin\alpha\sin\frac{\varphi}{2}) = 0 \end{cases} \tag{5}$$

2.2 Establishment of Cutting Mechanics Model

Drill cutting force comes from two aspects [2], the one is the role of rock under the action of elastic deformation and plastic deformation occurred in the process of resistance, and the other, the friction resistance between the rock and the cutter surface. Specifically, the force of the bottom rock on the

PDC cutter mainly occurs in two parts: First, the occurrence of plastic deformation, has not yet come into contact with the toothbrush on the diamond surface (A, B face) positive pressure F_{nf1} and Friction F_{nf2};Second, the lateral force of the rock on the side of the cutter (ie, the cylindrical surface of the cutter, which corresponds to the flank of the metal cutting tool) applies the normal force along the normal direction of the cutting surface and the friction in the direction parallel to the cutting speed. as shown in Figure 2.



(a) (b) (c)

Fig2. The force diagram of the rock on the ridge

1. The vector equation of the cutting load

Assuming that the bit speed and the unit drilling depth in unit time are constant, the drill bit and the cutting cutter are balance in the force, then the vector balance equation of the force F of the bit body applied the cutter and the force of the rock on the cutting cutter can be obtained.

$$\overrightarrow{F_{nb}}+\overrightarrow{F_{fb}}+\overrightarrow{F_{nf1}}+\overrightarrow{F_{ff1}}+\overrightarrow{F_{nf2}}+\overrightarrow{F_{ff2}}+\overrightarrow{F}=0 \tag{6}$$

2. Cutting force balance equation

Compared with the traditional PDC cutter, the ridge cutter surface rotation relative to the cutter ridge $(\pi-\varphi)/2$, the A face of the actual caster angle has been changed to α'_1, B face α'_2, so the cutting process is similar to A, B work Surface of the double-edged oblique cutting, the two edge inclined angles were λ_{s1}、λ_{s2}.In the oblique cutting process, the chip outflow direction is not in the direction perpendicular to the cutting width of the cross-section, but with this section to form an angle called ψ_λ, that is, the cutting surface of the chip out of the direction of the angle or debris angle, the chip flow angle of A , B face were $\psi_{\lambda1}$ and $\psi_{\lambda2}$, as shown in Figure 2 (b).

The main force, lateral force and normal force of the rock on the cutting cutter along the X, Y and Z axes can be obtained by projecting the force of the rock on the cutting cutter in the X, Y and Z directions. The force balance equation is:

$$\begin{cases} F'_d-F_{nf1}\cos\alpha'_1\cos\lambda_{s1}-F_{nf2}\cos\alpha'_2\cos\lambda_{s2}-F_{ff1}\cos\psi_{\lambda1}\sin\lambda_{s1}-F_{ff1}\cos\psi_{\lambda1}\sin\alpha'_1\cos\lambda_{s1} \\ -F_{ff2}\cos\psi_{\lambda2}\sin\lambda_{s2}-F_{ff2}\cos\psi_{\lambda2}\sin\alpha'_2\cos\lambda_{s2}-F_{fb}=0 \\ F'_c-F_{nf1}\cos\alpha'_1\sin\lambda_{s1}+F_{ff1}\sin\psi_{\lambda1}\cos\lambda_{s1}+F_{ff1}\cos\psi_{\lambda1}\sin\alpha'_1\cos\lambda_{s1}+F_{nf2}\cos\alpha'_2\sin\lambda_{s2} \\ -F_{ff2}\sin\psi_{\lambda2}\cos\lambda_{s2}-F_{ff2}\cos\psi_{\lambda2}\sin\alpha'_2\cos\lambda_{s2}=0 \\ -F'_n+F_{nb}+F_{nf1}\sin\alpha'_1+F_{ff1}\cos\psi_{\lambda1}\cos\alpha'_1+F_{nf2}\sin\alpha'_2+F_{ff2}\cos\psi_{\lambda2}\cos\alpha'_2=0 \end{cases} \tag{7}$$

F'_d, F'_c and F'_n are respectively the main cutting forces, lateral forces and normal forces of the cutting cutter, , and the vector sum is equal to the force of the bit on the cutter. By cutting the geometrical relationship of the cutter face, beveled cutting angle λ_s of the working face and the actual cutter caster angle α' can be calculated:

$$\begin{cases} \lambda_s=arc\cot\dfrac{\cos\theta\tan\varphi}{\sin\theta\sin\alpha\tan\varphi+\cos\alpha} \\ \alpha'=arc\cot\dfrac{\cos\alpha\sqrt{\cos^2\theta\sin^2\varphi+(\sin\theta\sin\alpha\tan\varphi+\cos\alpha)^2}}{\sin\theta\tan\varphi-\sin\theta\sin^2\alpha\tan\varphi-\sin\alpha\cos\alpha} \end{cases} \tag{8}$$

3. Broken rock mechanism of ridge cutter

At present, the mechanism of rock breaking is mainly studied by experiment or numerical simulation, combined with stress field of indenter (cutter) pressure into the rock, solid intrusion fracture theory and empirical analysis. The rock breaking mechanism of ridges is divided into two parts: static intrusion and cutting. Because of its cutter structure, it is difficult to obtain the solution of the stress field in the elastic body. Therefore, the numerical simulation is used to simulate the static intrusion and cutting process. Stress field distribution characteristics and solid intrusion fracture research results are used to analyze the two processes of rock breaking mechanism.

3.1 Numerical simulation analysis

1. Rock and ridge cutter model

Through the Proe to complete three-dimensional modeling, and then the import of abaqus software, The rock size of 40mm × 30mm × 16mm, uses C3D8R unit, the upper part of the grid size is 0.5mm. the lower part is 1mm; the size of the ridge cutter is Φ13.44mm × 12.5mm, the cutter angle is 135°, the same is used C3D8R unit, 0.4mm size. The rock is regarded as the elastic-plastic body, the elastic stage; the linear elastic constitutive model is adopted. The Drucker-Prager criterion is used in the plastic stage, and the equivalent plastic strain is used as the rock failure criterion. The ridge cutter is rigid body, the density is 3510kg / m3, the elastic modulus is 890Gpa and the Poisson's ratio is 0.07. After dividing the grid, the rock and the ridge cutter pattern are shown in Figure 3:

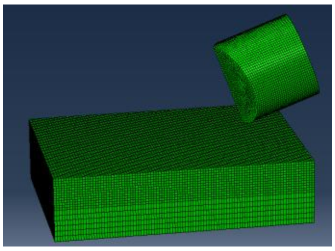


Fig3. The model of rock and ridge cutter

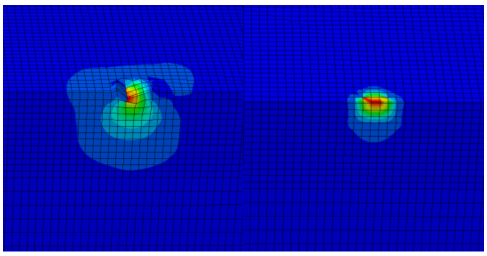
2. Boundary conditions and solutions

In the experiment, we need to simulate the two processes of the ridge cutter intrusive rock 2mm, and then cut the rock 20mm at the speed of 1m / s, in the analysis of step 1 to simulate the cutter invasion process, only the vertical movement of freedom, analysis step 2 simulation cutter Cutting the rock process, in the cutting process only the direction of freedom of the cutting direction, the restraint of the other five degrees of freedom, in all the process of rock bottom PINNED constraints. Set the relevant field variables and historical variable output.

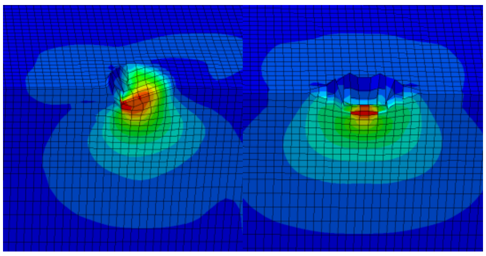
3. Simulation results analysis

(1) Analysis of the results of the intrusive process

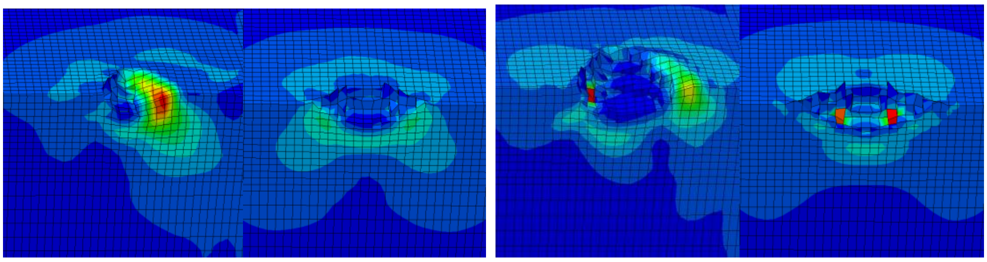
Firstly, the process of rock failure was simulated by 20°caster angle and 2mm cutting depth. The results were analyzed by stress state and failure form of rock. Fig.4 shows the stress of the rock at different moments, Fig (a) is the stress figure at the initial moment when the rock is subject to elastic compression, Fig. (b) is the stress figure of the rock at the ultimate strength, Fig. (c) shows the stress of the rock after the leap intrusion, Fig. (d) is the stress figure of a certain moment to continue to invade after the leap intrusion.



(a) T=0.0063s



(b) T=0.0075s



(c) T=0.0077s (d) T=0.0090s

Fig4. The tangential and lateral stress nephogram of rock under different moments

The above rock stress nephogram can be seen:

1) Rock and cutter contact area is just below a maximum stress area, and the shape was ellipsoidal.

2) The front cutter surface structure of the ridge cutter has little effect on the rock stress field before the leap intrusion of the cutter, but it can be seen that the tangential and lateral section of the cutter are large stress region in the process of continuous intrusion after leap intrusion. And the stress contours are parabolic. With the deepening of the intrusion, the tangential stress of the rock gradually increase and the lateral section stress decreases. The large stress region of the ellipsoid appears again under the contact area between the cutter and the rock.

3) The maximum stress area of the rock is not only the contact area between the cylindrical surface and the rock, but also the contact area between the cutter ridge, working surface and the rock.

(2) Analysis of the results of the cutting process

After completing the 2mm intrusion test in the ridge cutter, that is, the cutting of the rock the stimulating cutter at the speed of 1m / s. Figure 5 for the cutting process of the ridge cutter on the rock tangential force curve.

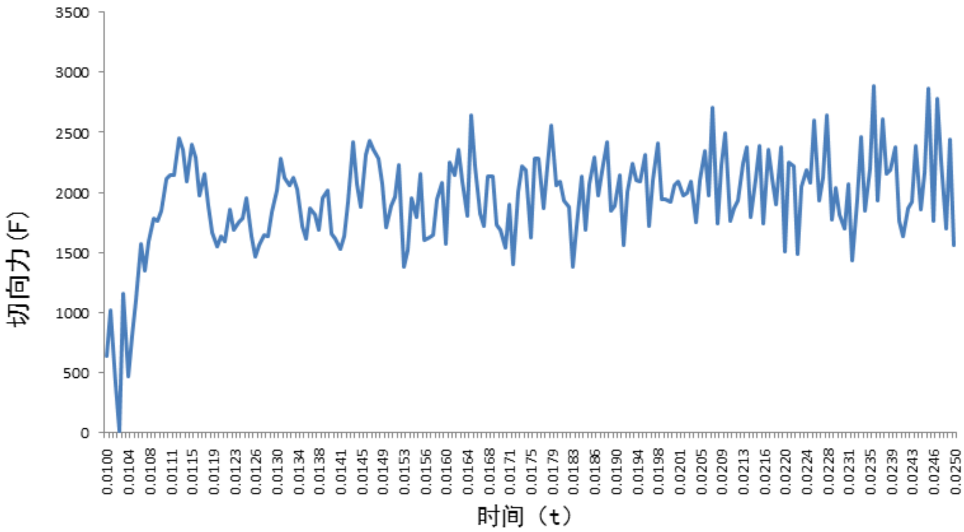
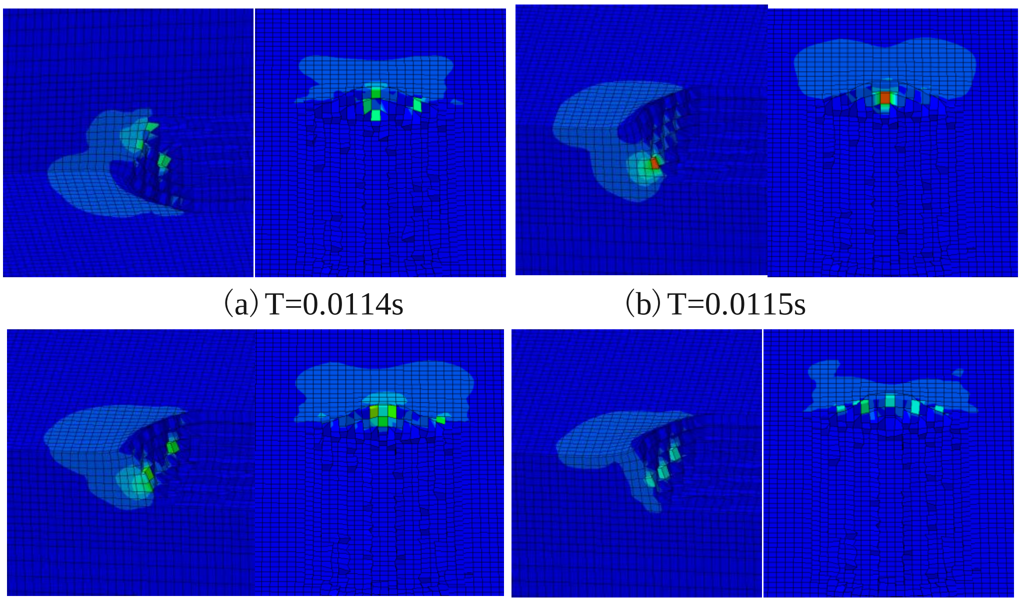


Figure 5. The ridge cutter on the rock tangential force curve of the cutting process

From the above curves, as the cutting load increases, it can be seen that the rock begins to break and the tangential force of the rock changes cyclically, which is the same as the change of tangential force when cutting the rock with conventional PDC. But the fluctuation amplitude is smaller, about 20% reduction; the cutting process is more stable and less vibration.

The change state of rock stress in a cycle of tangential force fluctuation is studied, and the variation law of rock stress field during cutting process is analyzed. Fig. 6 shows the tangent and plane stress nephogram of rock at different moments in one cycle of tangential force fluctuation. In order to better observe the plane stress of rock during cutting, the plane stress is the stress distribution after 1mm slice of rock surface.



(a) T=0.0114s (b) T=0.0115s

(c) T=0.0117s (d) T=0.0118s

Fig. 6 The tangent and plane stress nephogram of rock at different moments

From the above rock stress nephogram can be seen:

1) There are two stress zones in front of the contact area between the rock and the ridge.

2) The maximum stress zone appears in the front area of the contact between the ridge and the rock, and the shape is ellipsoid, similar to the ellipsoidal stress field formed by the rock during cutter invasion.

3) The trend of the main stress zone of the rock during the whole tangential force fluctuation period: the ridge line and the rock contact area → the ridge line and the rock contact front area → the ridge line, the working surface and the rock interaction area → the working surface and the rock contact area.

3.2 Analysis of broken rock mechanism in the invasion of ridge

The intrusion of the ridge cutter is one of the fields of the indentation of the indenter into the rock. According to analysis of rock breaking effect of the previous numerical simulation of intrusive rock, and through the research and experience in this field, and cutter spacing, disc cutter, stinger cutter and other tool rock breaking mechanism model [3-7], the breaking mechanism of the ridge cutter intrusive process to be elaborated.

According to the numerical simulation results, the rock breaking process is divided into three stages: deformation and initial crack formation, dense nucleation formation and crack propagation, and block collapse.

Deformation and initial crack formation stage

When the ridge cutter forces the rock, the edge of the ridge cutter first will contact with the rock. The contact causes extrusion stress. At a certain depth in the contact area, the maximum tensile stress is produced. The rock of cutter edge part under the action of tensile stress destroys and produces Hertz cracks. With the increase of the depth of invasion, the contact area between the side of the ridge and the rock increases rapidly, and the stress of the rock increases correspondingly. When the tensile stress reaches the tensile strength, the internal failure of the rock is localized and the initial crack is formed.

Dense nuclear formation and crack propagation stage

With the increase of the moving load, the compressed rock under the contact area crushes and destroys, and under the constant compression, the formation of ellipsoidal dense nuclear, similar to the "liquid" high stress sphere. So the surface of dense nuclear and the rock contact to form a tensile stress area. When the load increases, the stress in the dense nuclear will also increase. When the rock contact area of the dense nuclear and the tensile stress reaches the breaking strength, the rock around the dense nuclear forms a lateral crack, and the bottom position forms an intermediate crack.

The process of dense nuclear invading the rock, like a wedge, is pressed into the rock, and the dense nuclear under pressure continues to squeeze into the crevice in the formation of cracks, expands the crackdown to form a new crack. As the deep compressive stress compensates the tensile stress effect, the intermediate crack cannot develop infinitely in the depth, but the lateral crack is expanding under the action of tensile stress.

(3) Block collapse stage

With the further increase of the load, the crack continues to expand, the formation of crack initiation, and with the free surface through, leading to rock break into the broken, block collapse, complete a process of destruction. Then, the ridge cutter is again in contact with the rock, forming a compressive stress zone, starting the next compression failure process, as shown in Figure 4 (d) below.

3.3 Analysis on the mechanism of rock breaking during ridge cutter cutting

Through the numerical simulation and the result analysis of the ridge cutter cutting process, it can be seen that the crushing of the rock is similar to the squeezing and reciprocating process of rock extrusion, crack formation and macroscopic crushing.

It can be seen from Fig. 6 that as the tangential load increases, the middle of the cutter begins to squeeze the rock and the ellipsoidal stress concentration zone is formed in front of the contact between the ridge and the rock, which is similar to the high pressure dense nuclear in front of the area of contact between the cutter blade and the rock in the study of the breaking mechanism of the cutter [6] and the rock. Therefore, it can be determined that when the tangential load increases, the ridge line squeezes the rock to cause the rock to tensile failure, and crushes to form a high-pressure dense nuclear, and at the same time make the rock produce the Hertz crack as shown in Fig. 6 (b).The ridge line squeezes the rock at the same time, the two working surfaces are also squeezing the rock on both sides of the ridge to make the rock form a tensile stress zone at an angle. With the further increase of the tangential load, and under the action of lateral stress on both sides of the ridge and dense nuclear, the crack is further expanded until the free surface and the energy in dense nuclear is released. The volumetric fractures of rock on both sides of the ridge are shown in Fig. 6 (c) and (d).

Compared with the traditional PDC cutter shear broken rock, the ridge cutter is different which lies in its unique ridge-like cutter surface structure, in the cutting, the ridge line and the first contact with the rock and make it broken, and then through the cutter surface of the rock shear effect, so that the use of ridge cutter with a small cutting force can be reached as the same damage effect of ordinary PDC cutter does.

4. Conclusion

(1) Through the coordinate system, the establishment of the basic theory of the ridge cutter geometry has completed.

(2) The mechanical analysis of the ridge cutter cutting process was carried out, and the cutting mechanics model of the ridge was established.

(3) The model of the ridge cutter intrusion and cutting rock was established according to ABAQUS, simulating the ridge cutter intrusion and rock cutting process, and the results were analyzed.

(4) Based on the numerical simulation and theoretical analysis, the mechanism of rock fracture and the mechanism of rock breaking in the cutting process are mainly based on the tensile fracture and shear failure.

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