Study on Damage Law of Rock By Pdc Cutter Cutting

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Abstract

Rock crushing takes the form of continuous development and propagation of cracks. By studying damage law of PDC tooth cutting rock, it can provide theoretical basis for the scientific design and teeth layout of PDC bit. Based on the explicit dynamics solving method and the dynamic damage constitutive model, this paper establishes the finite element model of PDC teeth breaking rock. According to the simulation results, the development and damage of rock cracks during the rock breaking process of PDC teeth are divided into four stages: crack initiation, crack propagation, chip nucleation, and block cracking,and Through numerical simulation, the influence of rake angle and depth of cut on the damage rule of PDC rock breaking is analyzed. The research results provide a theoretical basis for improving the design of bit and improving the development of rock breaking theory.

Keywords

PDC cutters; damage law; crack propagation; rock-breaking mechanism; numerical simulation.

1. Introduction

The interaction between PDC and rock is a complex process. Cook et al.[1] simulated the process of PDC intrusion into rock on the basis of finite element software in two dimensions, and compared the simulation results of this method with the test results, and obtained the influence law of confining pressure on the pressure head into rock.Understanding the rock fracture mechanism under the action of load is the key to promote the research of rock breaking theory and the development of bit design technology. By using the finite element method, kuang yuchun et al.[2] established the mathematical model of PDC bit cutting rock, analyzed the cutter torque and bit pressure distribution under different rotating speeds, and predicted the torque and drilling pressure distribution trend of bit cutting teeth. Su O, Akcin N A studied [3] studied the mechanical properties of PDC bit cutting teeth in dynamic drilling process through discrete element method, analyzed the influence law of different cutting methods and different geomorphic rocks on rock-breaking effect, and studied the "aggressive" and crushing specific energy in the process of cutting rock. Chen c. -S et al.[4] analyzed the crack initiation Angle and crack growth path based on the boundary element method and the maximum tensile stress criterion. T O Pryhorovska et al.[5] demonstrated that there was no essential difference between linear cutting and circular cutting by establishing the finite element model of interaction between PDC bit tools and rocks. Through the experiments of PDC and rock cutting, Wang J[6]discussed the relationship between the cutting area, cutting speed, forward Angle and rock performance of PDC cutter.Based on the experimental data, a new model of interaction between PDC cutter and rock is established.

At present, most of the researches focus on the analysis of various parameters of PDC tooth breaking rock by numerical simulation. There are few researches on the damage law of rock damage during PDC tooth transient rock breaking process. In order to solve the difficulty in studying damage of experiment and simulation, and to reveal the fracture process and damage rule of rock under the

transient action of PDC teeth, Based on explicit dynamics and dynamic damage constitutive equations, a finite element analysis model for capturing rock damage details and fracture processes was established. The rock crack development and fracture process during the PDC fracture process are analyzed. The effects of different cutting angles And cutting depth on rock damage are discussed, and the microscopic rock breaking mechanism of PDC teeth is further revealed.

2. Nmerical simulation model

2.1 Finite Element Analysis Software

Due to the inhomogeneity of rock and the complexity of the contact state, PDC tooth breaking is a nonlinear and large deformation problem. LS-DYNA is committed to analyzing finite element problems in nonlinear and transient dynamics. And LS-DYNA has significant advantages in solving nonlinear problems. Based on the above advantages, the study selects LS-DYNA as the finite element analysis and solving software[7].

2.2 Model Assumptions

Simulation analysis makes the following basic assumptions[8]:

(1) Because the contact time between PDC and rock is very short and the hardness of PDC is very large in the simulation, the wear of PDC rock breaking process is ignored and it is regarded as a rigid body.

(2) Since the forward distance is short and the spiral motion is not considered, the movement of the PDC in the model is simplified as a plane linear cutting.

(3) The cutting speed and depth of cut of the PDC tooth are constant (definitely eaten, fixed speed).

2.3 Simulation Geometry Model

To establish a geometric model for the rock, consider that the actual crushing process of the rock is continuously pressed to form a stepped crushing pit for cutting[9]. According to the description of the crushing pit by the static cutting model, it is assumed that the first contact surface of the PDC and the rock forms a 120° direction with the horizontal direction[10]. The angle of the rock model is 40mm*20mm*10mm, as shown in Figure.1.

Create a geometric model for the PDC cutters. Set the PDC diameter to 13.44mm and the thickness to 2mm according to the manufacturer's common dimensions.
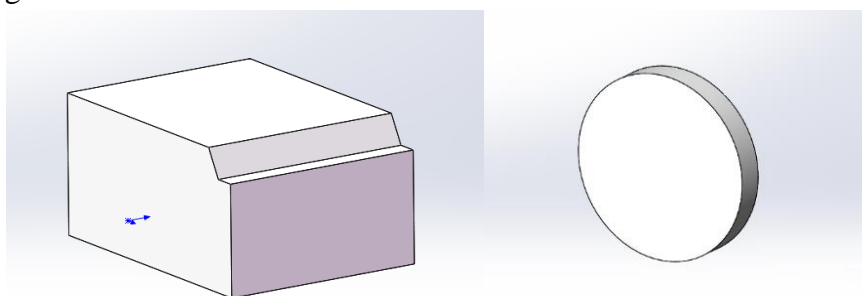

Figure.1. Rock and PDC tooth geometry model

2.4 Boundary conditions

First, setting full constraint on the rock floor. Second,the horizontal direction speed is applied to the PDC teeth to fix the longitudinal displacement of the PDC so as to realize the linear motion of the PDC under a fixed depth of cut.

2.5 Material properties

Because MAT_CSCM continuous cap model has a good effect in the study of rock cutting, and is widely used in engineering rock damage analysis, especially it has parameters such as rock fracture energy and damage index, it can accurately track elasto-plastic strain and fracture of rock. The process

used continuous cap model as the rock constitutive in this study[11]. According to literature materials and engineering experimental data[12], the rock and PDC corresponding material parameters are as shown in the table 1 and table 2.

Table 1 Nanchong sandstone attribute parameters

Modulus of elasticityGPa	Poisson's ratio	Uniaxial tensile strength，MPa	Shear strength，MPa	Density，kg·m-3	Internal friction angle
5.22	0.11	50.6	11.7	2540	34.5

Table 2 PDC cutter tooth material property parameters

Modulus of elasticity,GPa	Poisson's ratio density	Density，kg·m^{-3}
860	0.0768	3485

2.6 mesh division

The element size plays a very important role in simulating realistic debris and cracks. Sandstone grain size is typically 0.1mm to 0.5mm. In this study, the unit size of 0.1 mm was chosen to refine the rock mesh. A reasonable cell size allowed the simulation of rock fragments generated by the fracture without distorting the rock and forming realistic debris during the cutting process.

Element erosion patterns are susceptible to cell shapes. It is found that the hexahedral elements are usually accompanied by the discretization of the cells and a prismatic regular grid appears. Due to the highly regular nature of the hexahedral mesh, its use can distort the development of the fracture zone. In contrast, tetrahedral meshes are relatively random relative to a hexahedral mesh and are more suitable for simulating crack splitting and development during rock fragmentation[13]. As shown in Figure.2,the use of tetrahedral mesh to simulate the rock fracture process is more reasonable in this study's rock breaking simulation
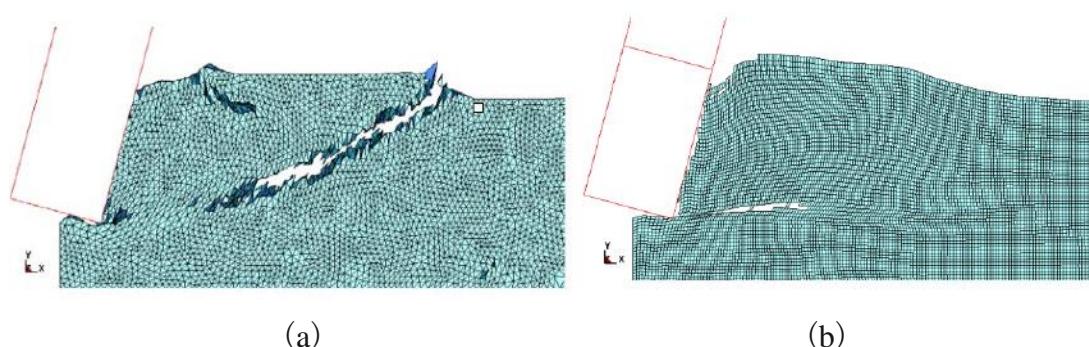

(a)　　　　　　　　　　　　　　　　(b)

Figure. 2. Comparison of different mesh types in the process of rock fragmentation simulation (a: tetrahedral mesh; b: hexahedral mesh)

In this study, the rock was used with a mesh size of 0.1 mm to accurately simulate the generation of cuttings and debris during the cutting process. For PDC cutters, a larger mesh size of 0.4 mm was used to speed up the solution and the tetrahedral elements were selected for the cell shape. After the success of the division, the number of nodes of the PDC tooth is 6834, the number of units is 30262, the number of nodes in the rock is 663561, and the number of units is 3405111, as shown in Figure. 3.
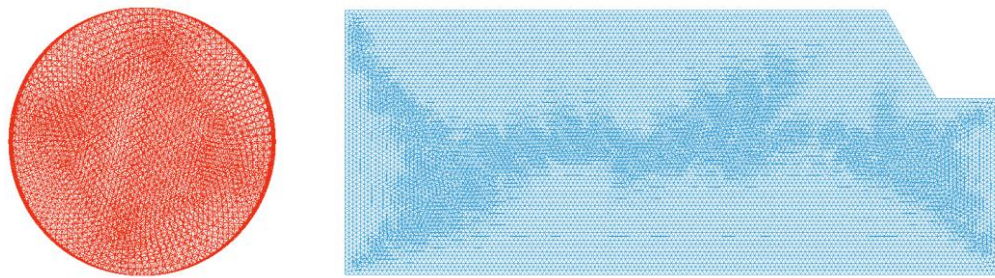
Figure.3. Rock and PDC Tooth Grid Model

3. Smulation results analysis

3.1 Rock Damage and Crack Analysis

This paper creates a geometric model of rock and PDC teeth, sets the working condition of the PDC tooth to cut the rock with a 15° rake angle, a 2.5 mm depth of cut, and a horizontal speed of 2 m/s, as shown in Figure.4.
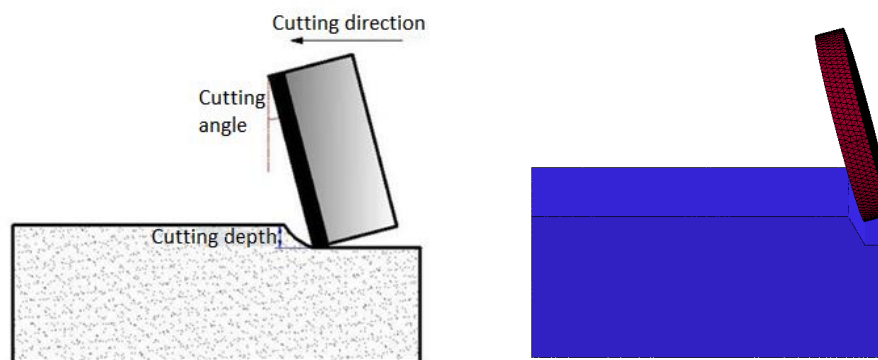

Figure.4. PDC rock breaking scheme and finite element model

Depending on the theory of damage mechanics, the continuous cap constitutive model defines the damage index to describe the degree of rock damage. As the element stress increases, when the stress or strain state of the element reaches a given damage threshold, the unit begins to damage. The corresponding damage index of this unit also begins to increase from 0. When it increases to 1, it is considered that the rock damage reaches the limit state, that is, the unit breaks the main crack and begins to propagate [11]. Therefore, by calculating the magnitude of the damage index, it is possible to simulate the extent of crack propagation and rock damage in rocks when PDC teeth cut rocks. According to the characteristics of rock fracture and crack development, this study divides the rock breaking process into four stages: crack initiation (compressive deformation), crack propagation, chip nucleation and block cracking.

(a) Crack initiation   (b) Crack propagtion

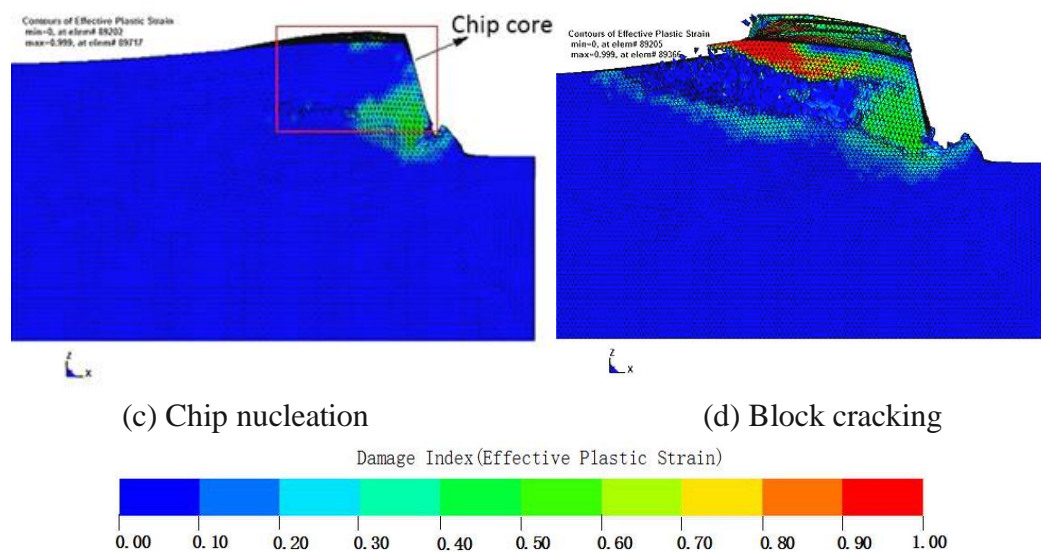(c) Chip nucleation   (d) Block cracking
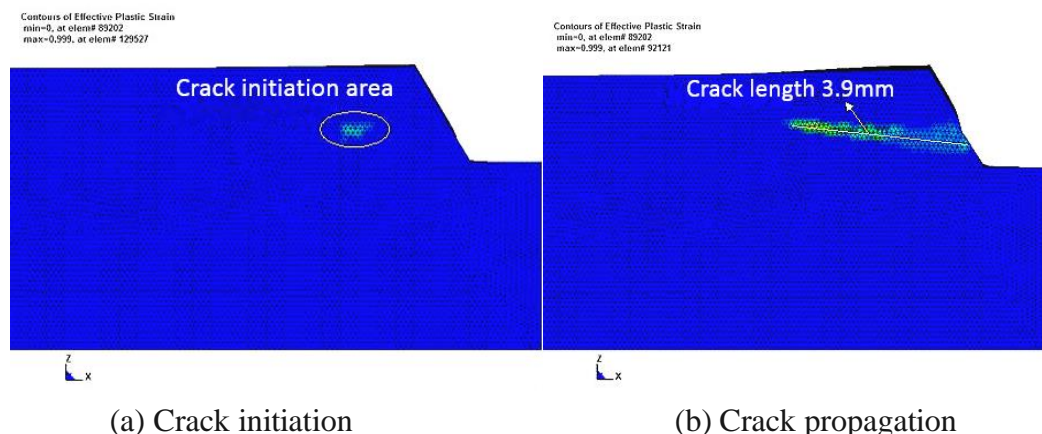
Figure. 5. Cloud of crack propagation and damage distribution during rock cutting

According to the simulation results, the stages of rock damage and crack propagation during rock breaking of PDC teeth are analyzed as follows:

1) crack initiation phase

When the loading begins, the cutting teeth perform horizontal movements in contact with the rock, and the contact rock acts on the three-direction pressure of the cutting force. Since the cutting force is smaller at this time, the compressive strength of the rock slightly increases and remains intact under the constraints of the surrounding rocks. And in the state of hydrostatic pressure, the rock directly under the tool is crushed and broken up to form a compression deformation zone, and the interior of the rock begins to crack, as shown in Figure 5-a.

2) crack growth stage

As the cutting load continues to increase, the microcracks extend into the interior of the rock and intersect to form cracks, which tend to develop toward the free surface. At this stage, the main damage zone of the rock is at the crack propagation point, as shown in Figure 5-b.

3) Chip nucleation stage

The contact cuttings are crushed to form the chip core, as shown in the red box in Figure 5-c. During the chip nucleation process, the degree and area of damage of the rock pressed by the tooth face increase, And most of the work done by the cutting force is converted into the surface energy of breaking debris and breaking away from the rock mass.

4) Blocking stage

As the cutting teeth are further fed into the rock, the development of cracks and the pressure exerted by the chip core have caused the rock to crack to a critical state. The crack sources infiltrate each other, the rock is sheared along the fracture, the volume breaks, and the degree of rock damage near the free surface is reached. The most serious (injury index exceeds 0.9), as shown in Figure 5-d. At the same time, due to the emergence of new space, a part of the compacted core flows out to the free surface and the load momentarily decreases, completing a leap-type cutting and crushing process.

Due to the strong regularity of crack formation in the rock model, it can clearly characterize the characteristics of rock fragmentation, such as the separation of rock fragments and the occurrence of rock fragmentation. It is a common method for rock damage research. According to the simulation results, the length of the two-dimensional crack at the rock section is taken as the research object, such as Figure 5-b shows.
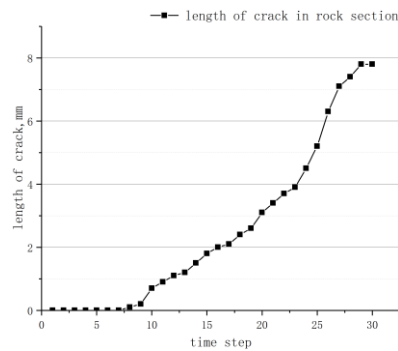
Figure.6. Rock crack length

From Figure 6, it can be seen that in the first 8 time steps, the rock forms a compressive deformation zone under the action of PDC tooth compression. This zone is the source of micro-cracking, and the small micro-cracks are continuously generated. The crack length is not easy to observe. Starting from the 10th time step, the crack propagated to 3.9mm. With the increasing degree of rock damage and cutting forces, from the 20th time step, cracks begin to form large cracks under the action of the shear force of the cutting teeth and quickly extend to the free surface, and the expansion speed linearly increases to 7.8mm. The volume is broken, as shown in Figure 5-d. With the end of the single-bounce crushing, the block body peeled off the rock matrix and the profile cracks had completely extended to the free surface.

3.2 Influence of different cutting parameters on damage law of rock-breaking

In view of the influence of different cutting parameters on rock-breaking damage law, due to a certain correlation between cutting depth and cutting Angle, this paper selected five cutting depth of 1mm,1.5mm,2mm,2.5mm and 3mm, corresponding to seven cutting angles of 0°, 5°, 10°, 15°, 20°, 25°and 30°.
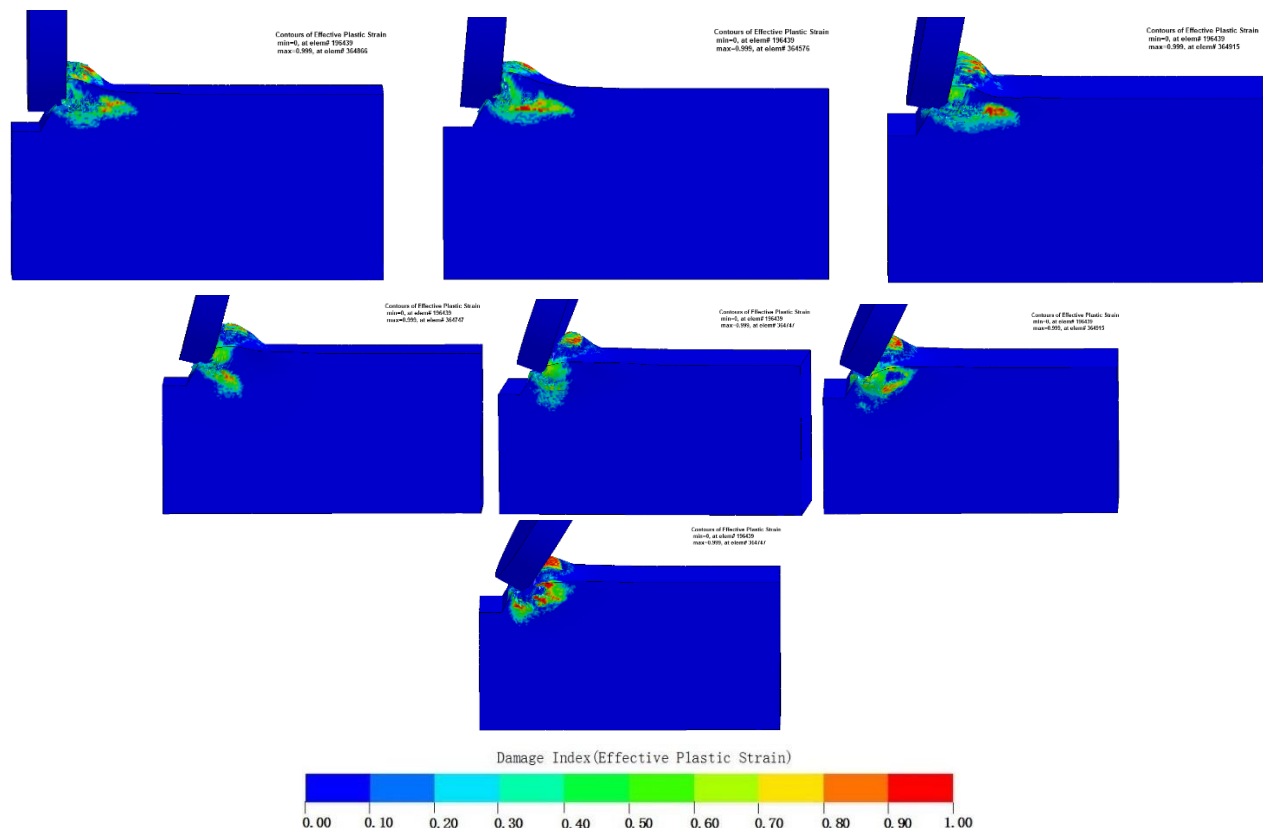

Figure.7. 1.5mm cutting depth, rock breaking process and damage cloud map with different front dip Angle
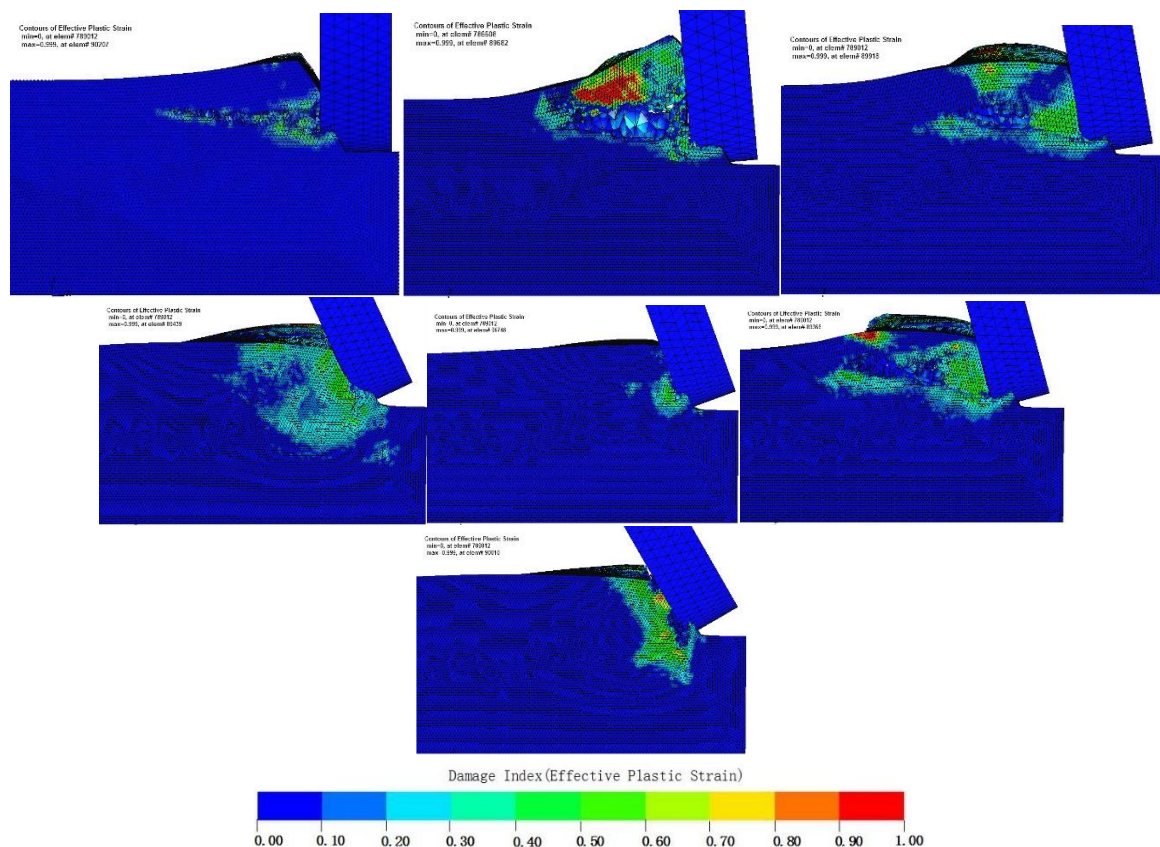
Figure.8. 2mm cutting depth, rock breaking process and damage cloud map with different front dip Angle

Figure 7 shows the rock damage cloud map of different front dip Angle at the same time step under the selection of 1.5mm cutting depth.Figure 8 shows the damage cloud map of rocks with different front dip angles at the same time step under the selection of 2mm cutting depth.The comparison between the two graphs shows more intuitively that within a certain range, the deeper the cutting depth, the heavier the damage to the rock.The front Angle is in the range of 0-15 degrees, the rock crack is longer, and it is easier to extend to the free surface,Rock-breaking is more effective.
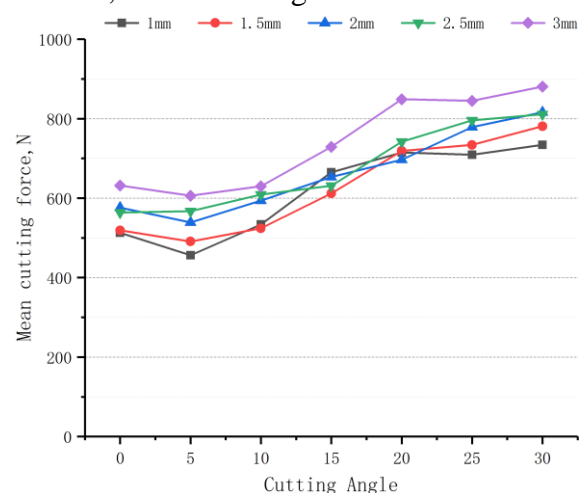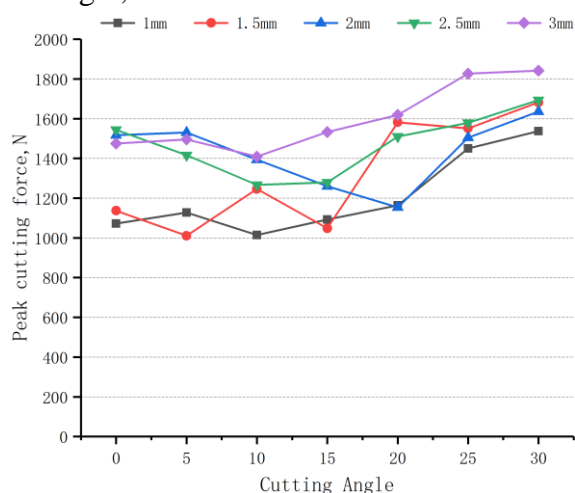

Figure.9.change curve of cutting force peak value   Figure.10.Change curve of mean cutting force
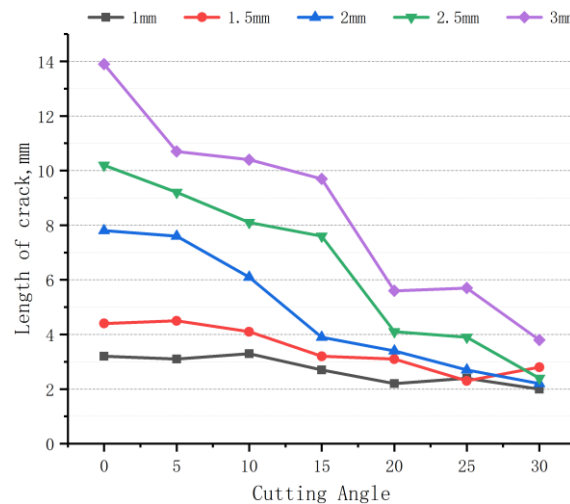
Figure.11.Change curve of crack length

A single leap in the process of crushing, different cutting depth and cutting force under different inclination angles as shown in Figure 9, the former Angle in 5 °~15°,cutting force peak is generally small. And with the change of cutting depth, the peak value of cutting force changes less. This shows that the former inclination in 5°~ 15 °，will reduce the impact load of the PDC teeth. Top rake in 15 ° to 30 °, PDC tooth peaks in the cutting force is bigger, the peak volatility is not stable, easy to break the PDC tooth, collapse, or even fall off from the drill bits.

The mean value of cutting force at different cutting depth and different forward dip Angle in a single stage of leaping forward crushing is shown in Figure 10.Former Angle in 0 ° ~ 10 °, average cutting force change is small, PDC tooth to break rock shear failure mode, data show that under the cutting parameters, PDC tooth wear is small. The cutting depth of 1mm, the forward Angle of 5 degrees, The mean cutting force is the smallest at 456N. When the former Angle is greater than 15 °, tooth cutting shear failure mode of rock gradually with the increase of Angle before changes to extrusion failure mode. The excessive front Angle makes the rock and the cutting tooth surface excessively extrude, the mean cutting force increases continuously, the chip core accumulates a large number of residues, and the crack length decreases gradually. At this time, a large amount of kinetic energy is consumed in debris removal during the cutter motion, and the high-frequency jumping type rock breaking cannot be effectively formed.

The length of the crack under different cutting depth and different forward dip Angle in the single leap forward crushing process is shown in Figure 11. In a certain range, the deeper the cutting depth, the larger the crack length value. he smaller the forward Angle, the larger the crack length.Single leap - forward crushing is more effective. Top rake in 0 ° ~ 15 °, the crack length change is more obvious, this is because the shear failure patterns help crack extension. his causes the rock to form a bulk fracture. But the former Angle is too small to 0°, crack began to rock deep development, is not easy to the free surface, increases the difficulty of breaking rock volume,and increases rock-breaking time. he cutting peak value and mean value of PDC teeth increased correspondingly, and the rock-breaking effect became worse. on't usually before using 0 ° .

Considering comprehensively, Under different cutting depth, the 5 ° ~ 10 ° former Angle, more conducive to the PDC cutter to eat into the formation and formation rock shear way, produce longer crack, finally enhance effect of rock fragmentation.

4. Conclusion

1) This study breaks through the limitations of traditional constitutive models in simulating rock damage, selects a continuous cap model for rock, and incorporates plastic damage parameters and elemental erosion schemes to successfully model a rock damage detail that can effectively simulate PDC teeth in rock interactions.

2) Based on the results of numerical simulation, the rock fragmentation process is divided into four stages: crack initiation, chip nucleation, crack propagation and block collapse according to the rock fragmentation theory. The rock breaking mechanism is analyzed by the damage angle.

3) In the single leap forward crushing process, the cutting force law under different cutting parameters was analyzed, and the rock-breaking law of PDC teeth at different cutting depth and cutting Angle was obtained, which explained the micro-rock-breaking mechanism of PDC teeth intuitively.

4) Based on the traditional research parameters, further analyze the crack development and fracture process of rock during PDC rock breaking from the perspective of damage and fracture. The results show, Under the same cutting depth, cutting Angle at 5 ° ~ 10 °, is advantageous to the PDC tooth form shear rock, crack easily to the free surface, shortening the period of a single leap type rock, forming high frequency leap to break rock.The final rock-breaking effect is the best.

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