

Numerical Simulation of Rock Breaking by Single Worn Cutting Tooth

Zejun Bao¹, Jincheng Wang², Chang Liu³

¹ Research Institute of Science and Technology Development, Southwest Petroleum University, Chengdu, 610500, China

² School of Southwest Petroleum University, Chengdu, Sichuan 610500, China

³ PetroChina Guangyuan Natural Gas Purification Co., Ltd, Guang Yuan 628400, China

Abstract: The cutting teeth on PDC bits have been working under wear for a long time, but the understanding of their rock breaking mechanism is not deep enough. In this paper, the influence of key factors such as wear height, passivation type, invasion depth, lithology, rake angle and tooth diameter on the load distribution of the cutting tooth edge, as well as the equivalent plastic strain form of the rock section, are investigated by means of numerical simulation. The results show that under the same rock breaking parameters, with the increase of wear height, the stress concentration at both ends of the cutting tooth edge is obvious, and the load in the middle section of the cutting tooth edge decreases with the increase of wear height, and the load fluctuation of the cutting tooth edge increases; The load on the tooth edge of the worn cutting gear decreases with the increase of the tooth diameter, and the fluctuation of the load on the tooth edge increases; The load distribution of the cutting tooth edge with an inclination of 15° is uniform, while the stress concentration at both ends of the cutting tooth edge with an inclination of 10° and the load drop at the middle section are obvious; Compared with the cutting teeth of the other two types of wear, the conventional wear cutting teeth have longer effective rock breaking length, larger load on the cutting edge, more uniform distribution and better rock breaking effect; According to the relevant simulation results, it is believed that the wear height, design parameters and wear types will affect the size and distribution of the tooth edge stress in the cutting process of worn cutting teeth, and then affect the wear trend in the cutting process. In addition, by observing the equivalent plastic strain form of the rock section after cutting, it is found that the rock cuttings under the action of new teeth are semicircular blocky, while the rock cuttings under the condition of worn teeth are flake. It is believed that the new teeth are more likely to form large blocky rock cuttings in the process of rock breaking, and the rock breaking effect is better than that of worn teeth.

Keywords: Worn cutter, Tooth edge stress, Numerical simulation, Plastic strain.

1. Introduction

The exploration and development of oil and gas, geothermal and deep mineral resources must rely on drilling technology. Rock breaking is the fundamental problem of drilling, and the drill bit is the most direct rock breaking tool. The research shows that although the bit cost only accounts for 3-5% of the drilling cost, its impact on the drilling cost can be as high as 70%. As a rock breaking tool for oil drilling, PDC bits account for more than 90% of the total footage of oil and gas drilling, up from 5% in the 1980s[1]. However, the drilling effect of PDC bit in deep difficult to drill formations is not ideal, one of the important reasons is the rapid wear of cutting teeth, which results in the reduction of specific pressure of cutting teeth, the inability to effectively eat into the formation, and the reduction of rock breaking efficiency. In fact, PDC bits are used in drilling, and the cutting teeth work under wear for a long time. The cutting load directly affects the rock breaking efficiency and service life of the bits. The main failure modes of PDC teeth are wear, fracture, delamination and spalling, and wear is the main failure mode of PDC teeth. The main wear modes of PDC teeth are abrasive wear and impact wear[2]. The research on PDC worn teeth by scholars at home and abroad mainly includes: Liang Erguo[3], etc. By simulating different section shapes, wear states and overlapping cutting states of cutting teeth, cutting experiments were carried out on a variety of rock samples with cutting teeth, and the influence laws of cutting area, contact arc length, back inclination angle of cutting teeth, rock anti drilling strength, wear height of cutting teeth and

other factors on the force of PDC cutting teeth were studied, and a comprehensive force model of cutting teeth was established; Zhu Guanghui[4] et al. analyzed the change of the three-way load on the cutting teeth under different rake angles and wear degrees, and the relationship between the wear degree and the temperature rise in the cutting process by using the selected cutting teeth to cut Wusheng sandstone on the planer; Wang Bin et al. systematically studied the wear form, wear mechanism and wear distribution of PDC bit cutting teeth after igneous rock use with electron microscope, and put forward suggestions on bit optimization.

As a prediction method, numerical simulation can solve the problems such as high experiment cost and difficult implementation, and greatly reduce the time cost. Therefore, using various finite element software to simulate the rock breaking process is one of the main technical means adopted by many scholars. Deng Minkai[5] and others established a rock breaking simulation model of PDC bit cutting teeth through abaqus software, and obtained the relationship between the force on the cutting teeth and the rake angle and side angle during single tooth cutting. They believed that the rock breaking effect was better when the rake angle was 15°~20°, and the rock breaking effect was better when the side angle was 5°; Peng Yaya[6] and others completed the numerical simulation and experimental research on rock breaking of PDC single tooth under the parameters of different rake angles, different side angles and different cutting depths. At the same time, they compared the results of numerical simulation with the experimental errors when taking Mohr Coulomb and Drucker Prager as the rock

constitutive models respectively, and obtained the conclusion that the error of D-P constitutive model is small and the efficiency of Mohr Coulomb constitutive model is high when using numerical simulation. At present, the research on the fracture mechanics of worn cutting teeth is not deep enough and systematic. Therefore, it is urgent to carry out the working mechanics analysis of cutting teeth under the wear condition.

2. Establishment of Numerical Model

In this paper, based on ABAQUS, a nonlinear dynamic model of the worn cutting tooth rock system is established. The size of the rock model is 50mm×90mm×40mm, and the cutting tooth thickness is 13mm, as shown in Figure 1. The rock model is discretized by using 8-node reduced integral (C3D8R). The worn cutting teeth need to divide the bottom worn part due to the irregular model, and refine the mesh of the area interacting with the cutting teeth. At the same time, a completely fixed constraint is imposed on the rock bottom, and a speed boundary of 0.25m/s is imposed on the cutting teeth[7]-[8].

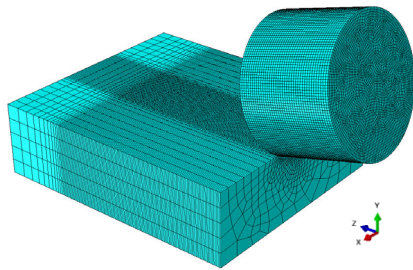


Figure 1. Finite element model of worn cutting tooth rock system

In the actual drilling process, the wear plane of the cutting teeth is usually parallel to the bottom scratch, so the wear tooth model of this simulation is based on this. The key structural parameters of worn teeth include rake angle, tooth diameter, wear height, passivation type, etc.

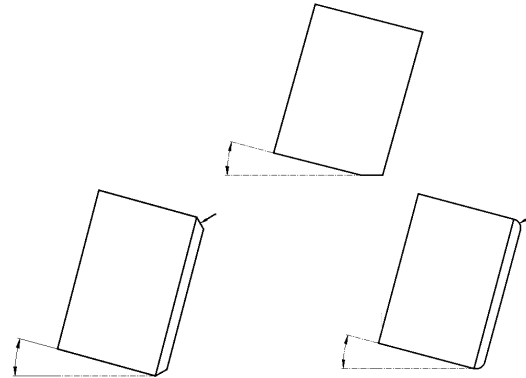


Figure 2. Worn tooth sample

2.1. Mechanical property parameters of rock

Lithology is a strong correlation factor affecting the cutting load and crushing efficiency of wear teeth. Typical sandstone, limestone and granite are selected as research objects to analyze the mechanical behavior of rock breaking by wear teeth. Rock size is 300mm×300mm×250mm. See Table 1 for main mechanical property parameters of rock for simulation.

Table 1. Mechanical property parameters of rock

lithology	Elastic modulus/Gpa	Poisson's ratio	compressive strength/Mpa	density/g/cm ³	internal friction angle/°
Sandstone	11.54	0.062	67.548	2.42	38.03
Limestone	31.2	0.171	105. 951	2.46	43.62
Granite	31.78	0.118	126. 519	2.73	45.29

2.2. Numerical simulation scheme

The process of rock breaking by worn teeth is affected by many factors, among which the main factors include wear height, rake angle, cutting tooth diameter, passivation type,

cutting depth, rock type, etc. In order to obtain the influence rule of each factor on cutting load in the simulation process, it is set as a single variable. In the passivation type, Y represents fillet wear and Z represents large chamfer cutting teeth. See Table 2 for specific simulation contents.

Table 2. Experimental scheme of single tooth cutting under wear condition

Experiment category	Wear height(mm)	Rock properties	Front inclination(°)	Tooth diameter(mm)	Cutting depth(mm)
Wear height	0.6/0.9/1.2/1.5	Sandstone	15	15	1.2
Front inclination	0.6	Sandstone	10/15/20	15	1.2
Tooth diameter	0.6	Sandstone	15	15/17/19	1.2
Wear type	Y/Z/0.6	Sandstone	15	17	1.2
Cutting depth	0.6	Sandstone	15	15	0.3/0.6/1.2/1.5
Rock properties	0.3	Sandstone/Limestone/Granite	15	15	1.2

2.3. Constitutive relation of rock

Rocks belong to granular brittle materials. The D-P (Drucker Prager) model is based on Coulomb Mohr model and Mises yield condition, and is derived from the classical D-P model. It is applicable to the case where the initial performance is isotropic when yielding occurs. Because it takes into account the intermediate principal stress σ_2 . The influence on the yield characteristics also takes into account

the property of shear induced expansion, so it is widely used in the study of rock fragmentation. Normal stress on octahedral plane for D-P yield criterion(σ_{Oct}) and shear stress(τ_{Oct}) represents intermediate principal stress(σ_2) Impact on rock failure [9]-[10]:

$$\tau_{oct} = \tau_0 + m\sigma_{oct} \quad (1)$$

$$\begin{cases} \tau_{\text{oct}} = \frac{1}{3} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \\ \sigma_{\text{oct}} = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \\ m = -\sqrt{6}\alpha, \quad \tau_0 = \frac{\sqrt{6}}{3}k \end{cases} \quad (2)$$

$$\alpha = \frac{2\sin\varphi}{\sqrt{3}(3 - \sin\varphi)} \quad (3)$$

$$K = \frac{6c\cos\varphi}{\sqrt{3}(3 - \sin\varphi)} \quad (4)$$

among $\sigma_1, \sigma_2, \sigma_3$ represents the maximum, intermediate and minimum principal stresses respectively; α and k are the internal friction angle with rock φ Coefficient related to viscosity coefficient c . Shear damage criterion is selected as the damage criterion of rock in this paper. Shear criterion is a phenomenological model, which can predict the damage initiation caused by the combined effects of nucleation, propagation and defects. The damage evolution rule is defined according to equivalent plastic displacement or fracture release energy. The characteristic length of the element is considered in both methods to reduce the influence of mesh division on the calculation results.

2.4. Simulation of rock breaking process

Along the cutting path, the characteristics of rock cuttings produced by new teeth and worn teeth are quite different, as shown in Figure 3. Although the two teeth can produce obvious volume crushing under the same conditions, the rock debris under the action of new teeth presents semicircular block shape, while the rock debris under the condition of worn teeth is flaked, which is consistent with the shape of rock debris observed in physical experiments. Generally, in the process of interaction between cutting teeth and rock, the starting point of rock damage crack is the tooth edge, and the change of tooth edge shape will inevitably lead to the change of rock fracture surface.

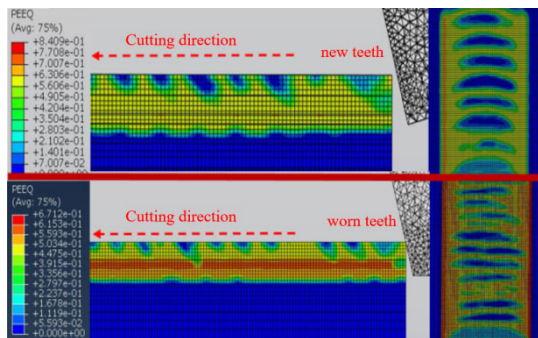


Figure 3. Equivalent plastic strain of rock section

3. Stress Analysis of Worn Tooth Edge

In the process of rock breaking, the cutting edge of the cutting tooth on the drill bit is the starting point of rock breaking and the starting point of cutting tooth wear. Therefore, the load distribution on the tooth edge has always been the focus of researchers, which is helpful to predict the wear trend of worn cutting teeth.

In the process of rock breaking, the contact area between

PDC teeth and rock changes at any time, so the instantaneous stress distribution on the cutting tooth edge is random. In order to accurately study the rule of cutting load distribution of cutting teeth, programs are compiled with the help of the PDE platform (Python Development Environment) in ABAQUS software to calculate the average stress of each node of worn teeth in the cutting process. Figure.4(a) and Figure.4(b) are the mean stress nephogram and the instantaneous stress nephogram respectively. In the rock breaking process of cutting teeth, only part of the cutting edges participate, so it is not necessary to extract all the node stresses on the cutting edges. The extraction range of tooth edge nodes is shown in Figure.5. The green part is the main part of the node extraction in this paper.

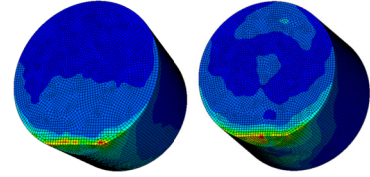


Figure 4. Stress nephogram of cutting tooth surface

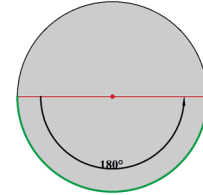


Figure 5. Output range of tooth edge node area

3.1. Stress of tooth edge under different wear heights

The change of node stress on worn tooth cutting edge with wear height is shown in Fig.6. When the wear height is small, the stress of the nodes on the cutting edge of the cutting gear is relatively average. With the increase of the wear height, the load fluctuation on the cutting edge increases, and the stress concentration on both sides of the wear edge is obvious. The more severe the load fluctuation on the tooth edge is, the easier the tooth breakage will occur. That is, with the increase of the wear height, the greater the risk of further wear of the cutting teeth.

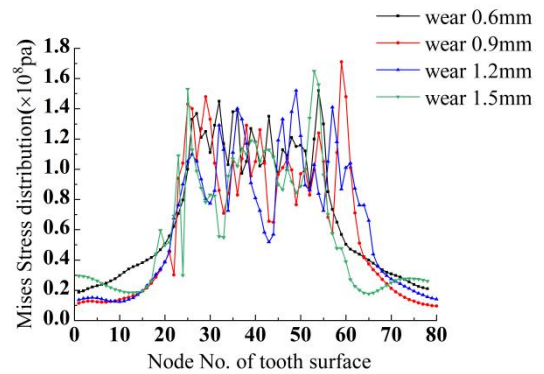


Figure 6. Node stress of tooth edge under different wear height

3.2. Stress of tooth edge at different inclination angles

With the increase of the rake angle, the squeezing effect of the working face of the cutting gear on the rock is enhanced, and the stress on the cutting edge of the worn gear increases

with the increase of the rake angle, as shown in Figure.7. When the inclination angle is 15°, the load on the tooth edge node is relatively stable, and when the inclination angle is 10°, the stress concentration on both sides of the cutting tooth edge is relatively obvious, which may be the starting point for the cutting tooth to increase wear.

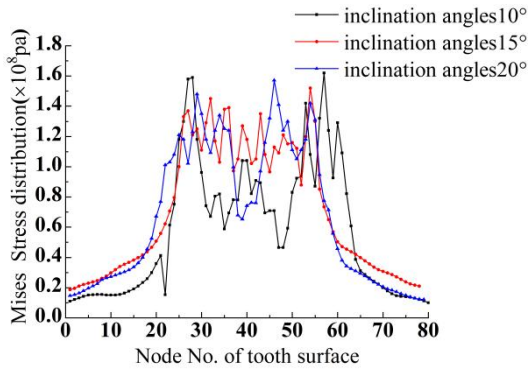


Figure 7. Node stress of tooth edge under different inclination

3.3. Stress of tooth edge under different tooth diameters

Under the same cutting conditions, the load on the cutting edge of worn teeth decreases with the increase of tooth diameter, as shown in Figure.8. When the diameter of the cutting tooth is 15mm, the load distribution on the tooth edge is relatively stable, and the load fluctuation starts to intensify with the increase of the tooth diameter. This is because, under the same conditions, the increase of the tooth diameter increases the wear plane, which reduces the ability of the cutting tooth to invade the rock.

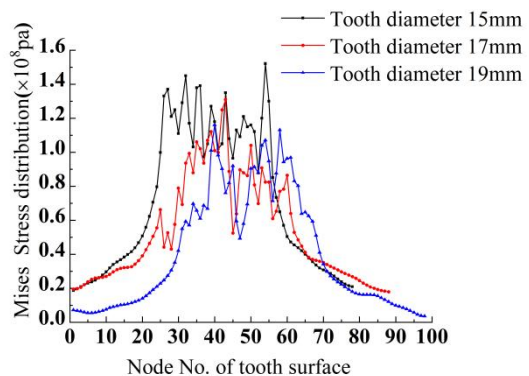


Figure 8. Node stress of tooth edge under different tooth diameters

3.4. Stress of tooth edge under different wear types

Under the same cutting conditions, the load on the conventional wear tooth edge is the largest, and the high value stress area is wider. In this case, the conventional wear tooth edge still has a strong ability to scrape and cut rock. Compared with the cutting teeth with large chamfer and fillet wear, the former has smaller specific pressure of the tooth edge node and poorer invasiveness. From the stress nephogram of cutting teeth, it can be found that the tooth edge on the fillet worn tooth changes from a straight line of the conventional tooth edge to a circular arc surface, resulting in a wider range of high value stress distribution and a lower specific pressure value at each stress node.

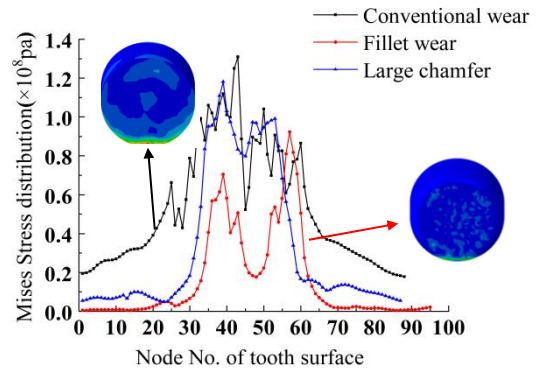


Figure 9. Node stress of tooth edge under different wear types

3.5. Stress of tooth edge under different cutting depths

The change of stress of worn tooth edge with cutting depth is shown in Fig.10. The stress of the cutting tooth edge is positively related to the cutting depth. With the increase of the cutting depth, the effective rock breaking width of the cutting tooth becomes longer. However, when the cutting depth reaches 1.5mm, the stress in the middle of the tooth edge decreases, and the load fluctuation increases significantly, which is basically consistent with the changing law of cutting load in single tooth cutting.

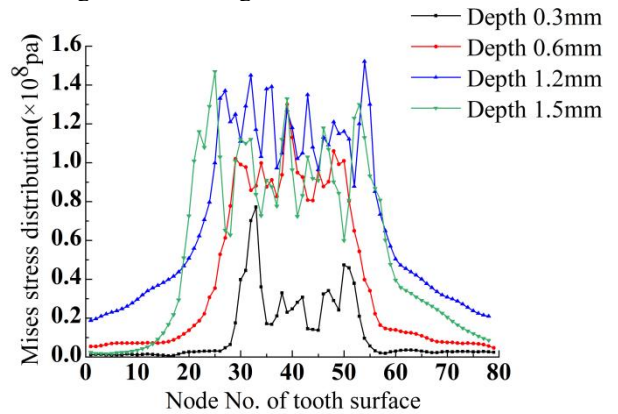


Figure 10. Node stress of tooth edge under different cutting depth

3.6. Stress of tooth edge under different lithology

The change of node stress on the cutting edge of worn teeth with rock properties is shown in Fig.11. Under the same cutting conditions, the law that the stress on the tooth edge changes with the lithology is highly consistent with the law that the tangential load changes with the lithology in the single tooth cutting experiment, that is, the stress on the tooth edge increases with the increase of rock strength. With the increase of rock strength, the load required for invading the same depth is correspondingly increased, and the load fluctuation on the tooth edge is more severe, resulting in increased wear or tooth breakage.

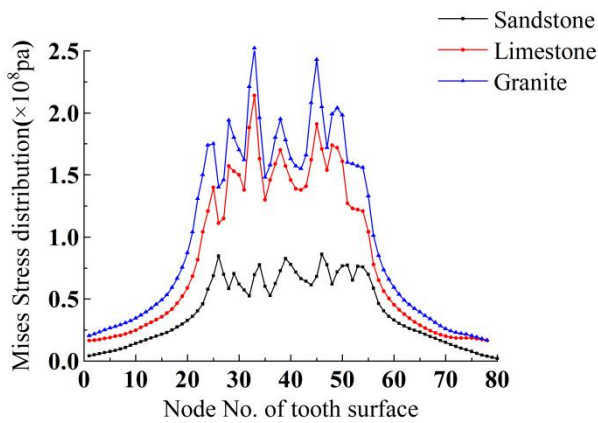


Figure 11. Stress of tooth edge node under different rocks

4. Conclusion

(1) With the increase of the wear height, the stress concentration effect at both ends of the cutting tooth edge is obvious, and the load in the middle section has a downward trend. At the same time, the wear height will affect the load fluctuation of the cutting tooth edge. The higher the wear height is, the stronger the load fluctuation of the cutting tooth edge will be. Therefore, with the wear of the cutting tooth on the drill bit during the drilling process, its ability to eat into the formation will weaken, and the drill bit vibration will intensify.

(2) By comparing the load on the worn cutting edge with the same wear height and different inclination angles, it is found that the load on the cutting edge is more uniform when the inclination angle is 15° , and the load fluctuation on the cutting edge is not obvious; For the worn cutting teeth with an inclination of 10° , the load stress concentration at both ends of the tooth edge is obvious, and the load fluctuation on the tooth edge is more severe than that of the cutting teeth with an inclination of 15° . It is believed that under the same wear condition, the cutting teeth with an inclination of 15° have better rock breaking effect and more stable rock breaking energy.

(3) With the increase of the tooth diameter, the stress of the cutting tooth edge has a downward trend, and the effective rock breaking width of the tooth edge becomes narrower, and the load fluctuation is intensified. By comparison, under the same wear conditions, the cutting tooth with the tooth

diameter of 15mm has better rock breaking ability and more stable rock breaking effect.

(4) By comparing the equivalent plastic strain diagram of the rock section, the rock debris generated during the cutting process of the worn cutting teeth is flaky, while the rock debris generated during the cutting process of the non worn cutting teeth is blocky. It is believed that the new teeth have stronger rock crushing capacity than the worn teeth.

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