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Study on Rock Breaking Efficiency of Non Planar PDC Teeth

Ling Feng

School Chengdu Technological University, Chengdu 610000, China

Abstract: In order to explore the law of rock breaking efficiency of existing non planar teeth in sandstone, indoor single tooth rock breaking experiment and numerical simulation of rock breaking are carried out for planar teeth, sharp circular teeth and axe teeth, and the effects of different eating depth and rake angle on rock breaking efficiency of PDC teeth are analyzed. Compare the experimental results with the simulation results. Firstly, for the trend, the trend of the experimental results and the simulation results is the same. Secondly, through the extraction and comparison of the data, the maximum error of the data is 9% and the minimum error is 1%. Therefore, it is considered that the analysis result is true and the analysis method is effective. The results show that increasing the feed depth of PDC teeth will increase the cutting force of PDC and the volume of broken rock; Under the same conditions, the volume of rock broken by plane teeth is larger than that of axe teeth and sharp circular teeth; Under the same conditions, the cutting force of axe tooth is greater than that of the other two teeth. For plane tooth, the best working condition of broken sandstone is raking angle of 15 ° and depth of 1mm; For sharp round teeth, the best working condition of broken sandstone is rake angle of 5 ° and draft depth of 2mm; For axe teeth, the best working condition of broken sandstone is rake angle of 20 ° and draft depth of 3mm; Comprehensively comparing the effect of three teeth in crushing sandstone, the axe type has the best crushing effect.

Keywords: Non Planar Teeth; Indoor Single Tooth Experiment; Numerical Simulation; Eat Deep; Rake Angle.

1. Introduction

PDC drill bits are currently the most commonly used drill bits, and their performance in deep formations or some difficult to drill formations is superior to other drill bits. However, compared to themselves, their rock breaking efficiency in the aforementioned formations is reduced [1-3]. Therefore, studying the influence of non planar teeth on rock breaking efficiency is of great significance for improving the rock breaking efficiency of PDC drill bits.

Zhai Yinghu et al. [4] found during the single tooth rock breaking experiment that the magnitude of the cutting load is influenced by the size of the tooth contact area, and the magnitude of the cutting force affects the axial force. After conducting a single tooth experiment, Liang Erguo [5] found that for non planar teeth, the longer the arc of the non planar teeth, the greater the cutting force when the contact area of the teeth is the same; At the same time, the stronger the drillability of rocks, the greater their cutting force. Tian Feng et al. [6] used mathematical methods to establish the relationship between cutting area and crushing volume. After the single tooth rock breaking experiment by Wang Jiajun et al. [7], it was found that when the depth of PDC teeth is constant, the cutting force of the cutting teeth will also increase with the increase of the rotary table speed. Zhu Xiaohua et al. demonstrated through single tooth scraping experiments that the larger the cutting angle of PDC teeth, the higher their rock breaking efficiency, and as the confining pressure of the rock increases, the difficulty of rock breaking also increases. Hertz [9] studied the contact between PDC teeth and rock using elastic contact theory, and concluded that when the contact load between two objects reaches a critical value, the rock will produce conical cracks and expand downwards to form an open state, which can explain the initial state of PDC feeding into the rock. After conducting rock experiments, MENDOZA et al. [10] found that when the strength of the rock is high, the particles that break the rock will have an impact on the remaining strength of the rock. ZEUCH[11]found during the depth experiment that changes in depth can affect the development of rock cracks. Gomez [12] conducted induced damage experiments on rocks and found that the application of induced loads has a significant impact on the static splitting strength of rocks and reduces their dependence on the direction of damage. GLOWKA et al. [13] found during the experiment that the frictional force generated during the cutting process significantly reduces the lifespan of PDC teeth. RASHIDI et al. [14] conducted research on drill bit selection using the ROP model, incorporating conventional drilling parameters into the model and establishing reliable output data for drill bit selection analysis. JOHNSON [15] developed a new type of non planar PDC cutting teeth, which discharge rock debris through high and low surfaces during rock fragmentation.

In summary, research on PDC teeth mainly focuses on the contact relationship between the teeth and the rock, as well as the relationship between the contact arc and cutting area of PDC cutting teeth and the rock breaking efficiency. However, the above cutting principles or the development of a new type of cutting tooth require a significant investment of manpower, resources, and time. Compared to the development of new types of teeth, few people have studied the rock breaking efficiency of existing concentrated tooth shapes. Therefore, this article takes the commonly used PDC as the research object, studies a rock breaking law of existing teeth, and provides ideas for the subsequent layout of PDC drill bits.

2. Indoor Single Tooth Rock Breaking Test

2.1. Experimental Establishment

In the actual drilling and rock breaking process, the drill bit rotates and moves axially around the centerline of the drill string, while the PDC teeth located on the drill bit rotate around the centerline of the drilling direction. Due to the shallow depth of the PDC drill bit entering the formation, the depth at which a single PDC tooth rotates and invades the formation is basically the same. Therefore, when conducting a single tooth experiment, the motion process of the PDC tooth is simplified to a fixed depth linear cutting motion, as shown in Figure 1. The rock used in the experiment is Wusheng sandstone, with flat teeth, pointed circular teeth, and axe shaped teeth. The experimental equipment, rock, and cutting teeth used in the experiment are shown in Figure 2.

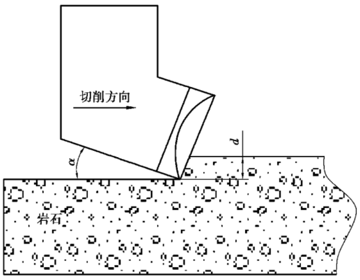


Fig 1. Simplified model of PDC tooth rock interaction

Fig 2. Single tooth rock breaking equipment and rock

The PDC teeth are mainly subjected to axial force, tangential force, and radial force during the rock breaking process. The tangential force is opposite to the direction of the cutting teeth (i.e. cutting force), and the axial force is along the direction of the drill bit axis (i.e. reflecting drilling pressure). The radial force is perpendicular to the tangential force and axial force. In the processing of experimental results, the tangential force and axial force are mainly processed.

In actual drilling operations, in order to evaluate the crushing efficiency of a drilling tool or a drilling tool, we use the crushing specific work to evaluate it. Crushing specific energy refers to the energy consumed to break a unit volume of rock. The smaller the value, the lower the energy required for the tool or method to break a unit volume of rock. For crushing volume, it can be divided into two types: theoretical crushing volume, and the calculation of crushing specific work is based on the area projected by PDC teeth on the rock multiplied by the crushing distance; The true fractured volume refers to the actual volume of rock that falls off during the process of rock breaking. So the expression for crushing specific work is:

$$MSE_r = \frac{W}{V_r} \quad (1)$$

In the formula: MSE_r is the actual crushing specific work; W is the energy required for rock breaking; V_r for the true shattered volume.

2.2. Analysis of Experimental Results

The experiment mainly involves three types of tooth shapes, with experimental conditions controlled at a forward inclination angle of 10°and 15°, and an insertion depth of 1mm and 1.5mm. For the processing of experimental results, the main focus is on four indicators, namely tangential force (cutting force), axial force (drilling pressure), volume of fractured rock, and specific work of fragmentation. The image shown in Figure 3 is the PDC tooth scraping experiment. In the experiment, sensors were used to measure the tangential and axial forces during rock breaking. The volume of the fractured rock was calculated using the collected rock mass, and according to formula (1)

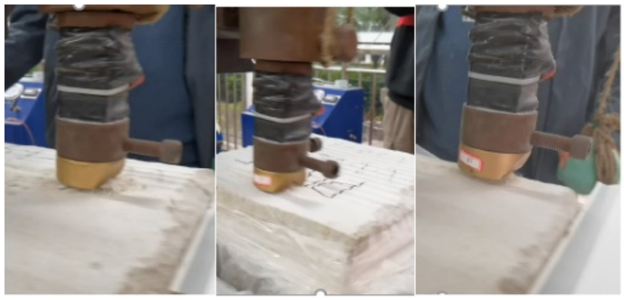


Fig 3. Rock breaking pictures of three kinds of teeth

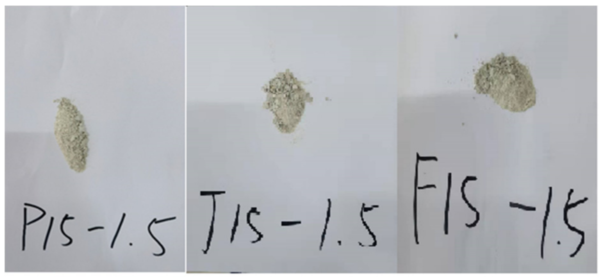
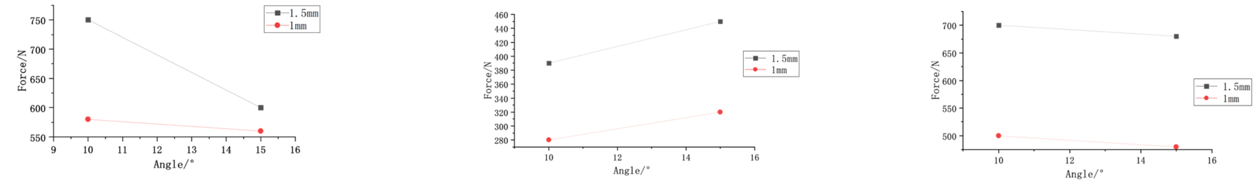


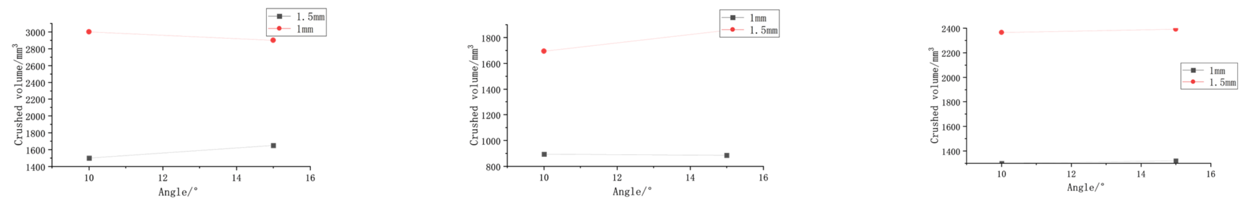
Fig 4. Rock cuttings broken by three kinds of teeth

The cutting diagrams of three types of teeth for rock breaking extracted from experimental data are shown in Figure 5. From the graph, we can see that as the depth of penetration increases, the cutting force of each tooth increases. When the rake angle of PDC teeth is increased, the cutting force of flat teeth and axe teeth decreases, while the cutting force of pointed circular teeth increases. This means that increasing the rake angle of pointed circular teeth will increase the energy of rock fragmentation. As shown in Figure 7, increasing the depth of PDC teeth will lead to an increase in the volume of fractured rock when three types of teeth are used to break the rock. For flat teeth and pointed circular teeth with a depth of 1mm, increasing the forward inclination angle of the teeth increases the volume of fracture, while in other cases, the volume of fracture of the teeth decreases. From the perspective of fractured volume, planar teeth have the highest volume of fractured rocks. As shown in Figure 8, increasing the depth of penetration will result in a decrease in the crushing specific work of the three types of teeth when breaking rock; Except for sharp circular teeth, increasing the forward inclination angle of the teeth will reduce the specific crushing power of the teeth, that is, increase the rock breaking efficiency. From a horizontal perspective, the crushing efficiency of pointed circular teeth is the highest, which means that for fractured sandstone, pointed circular teeth are the most suitable.



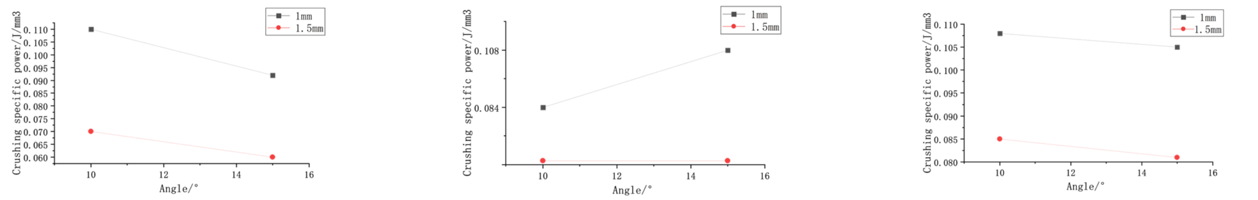
(a)Plane tooth (b)Sharp round tooth (c)Axe tooth

Fig 5. cutting force of different PDC teeth



(a)Plane tooth (b)Sharp round tooth (c)Axe tooth

Fig 6. broken rock volume of different PDC teeth



(a)Plane tooth (b)Sharp round tooth (c)Axe tooth

Fig 7. crushing specific work of different PDC teeth

3. Finite Element Analysis Model

3.1. Establishing a Model

According to Saint Venant's theorem, taking into account the computing power of the computer, the size of the rock model is set to. As the purpose of the analysis is to benchmark experiments, the rock selected for this study is Wusheng sandstone.

The purpose of this analysis is to analyze the rock breaking patterns of existing non planar teeth. Therefore, the PDC tooth profiles used are planar teeth, ridge teeth, and pointed circular teeth, with a diameter of 15.88mm and a height of 13.2mm for each tooth. The material parameters are shown in Table 1.

In order to better benchmark the experiment, this simulation is based on linear cutting and the following assumptions are made:

(1) The rock is continuous and isotropic, without considering the influence of temperature on the rock;

(2) Neglecting the influence of rock debris on subsequent cutting processes;

The finite element model established based on the rock breaking experiment is shown in the figure:

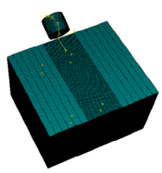


Fig 8. Finite element analysis model

In the analysis model, C3D8R mesh is used for both rock and tooth meshes, and mesh refinement is performed in the area where the rock is scraped. The global mesh density is 5, and the refinement mesh density is 0.5.

3.2. Rock Strength Criteria

The Drucker Prager yield criterion is a modified version of the Mohr Coulomb yield criterion, which takes into account the influence of confining pressure on rocks and the swelling caused by rock shear damage. In fact, the yield criterion is a criterion for describing whether a material has reached plastic damage, and the linear yield surface of the linear DP criterion model is shown in the figure.

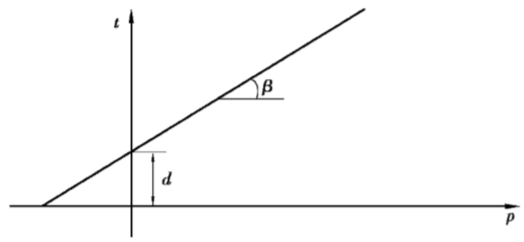


Fig 9. P-T relation curve in DP criteria

The formula for the linear DP criterion is:

$$F = t - p\tan\beta - d \quad (2)$$

$$t = \frac{1}{2}q\left[1 + \frac{1}{K} - \left(1 - \frac{1}{K}\right)\left(\frac{r}{q}\right)^3\right] \quad (3)$$

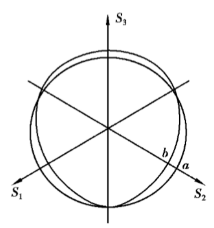


Fig 10. typical yield surface of linear DP model

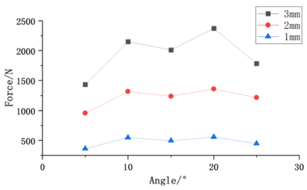
When defining the isotropic hardness of a material, the friction angle of the material can be obtained $\beta \le 71.5^\circ$, $\tan\beta \le 3$. When K=1 and t=q, the yield surface in the principal stress plane is a Mises circle, and the ratio K should be 1. However, in reality, the yield surface is an outward convex ellipse, so $0.778 \le K \le 1$.

3.3. Analysis Results

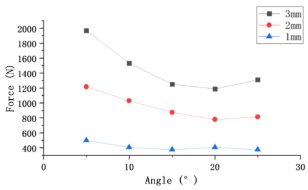
When analyzing, we also consider changing the two parameters of the teeth, namely the forward inclination angle and insertion depth. The forward inclination angle is 5°, 10°, 15°, 20°, and 25°, and the insertion depth is 1mm, 2mm, and 3mm. In actual single tooth rock breaking experiments, the scraping distance of PDC teeth is 300mm. However, in the numerical simulation process of PDC teeth, due to the limitation of computer computing power, the actual scraping distance is 50mm. Therefore, the calculation of crushing volume and crushing specific power in numerical simulation analysis is smaller than the actual value.

The simulation results of cutting forces for three types of PDC teeth are shown in Figure 11. Flat teeth: Increasing the depth of the flat teeth will lead to an overall increase in cutting force; After changing the rake angle of the planar teeth, it was found that the cutting force reached two peaks at 10°and 20°, and after passing the peak, the cutting force decreased. Sharp circular teeth are the same as flat teeth, increasing the depth of penetration will lead to an overall increase in cutting force. After changing the rake angle of the pointed circular teeth, it was found that the cutting force decreased from 5°to 20°, and there was a slight increase at 25°. Increasing the depth of the axe teeth will also improve the overall cutting force of the teeth. After changing the rake angle of the axe teeth, it was found that the peak cutting force of the axe teeth appeared at 15°, and then gradually decreased during the two changes. Comparing the cutting forces of three different teeth, it was found that the cutting force of the axe shaped teeth was greater than that of the other two teeth at three different depths. In the case of single finger aggression, the axe shaped teeth had stronger aggression.

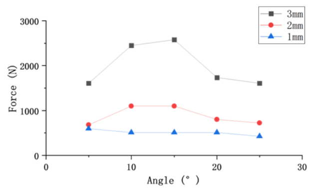
The simulation results of three types of PDC tooth crushing volumes are shown in Figure 12. For the three types of teeth, increasing the depth of penetration will lead to an increase in the volume of broken rocks for the three types of teeth. For planar teeth, increasing the rake angle at depths of 2mm and 3mm results in a decreasing trend in the volume of fractured rock. The peak value appears at 5° at 2mm and 10°at 3mm. But for a depth of 1mm, the maximum volume of broken rock occurs at 15°. For sharp circular teeth, the change in the volume of the entire fractured rock shows a triangular shape when the forward inclination angle is increased. The maximum value of the fractured rock volume occurs at 15°for all three depths. For axe shaped teeth, the change in the volume of the entire fractured rock shows a decreasing trend when the forward inclination angle is increased. The maximum value of the fractured rock volume appears at 5°for all three depths. Comparing the situation of three teeth comprehensively, under the same conditions, the volume of rock broken by planar teeth is greater than that of axe shaped teeth and pointed circular teeth.



(a)Plane tooth

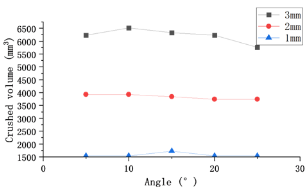


(b)Sharp round tooth

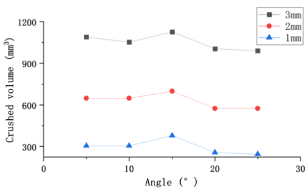


(c)Axe tooth

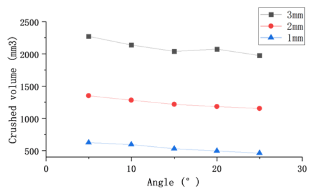
Fig 11. Cutting force of different PDC teeth



(a)Plane tooth

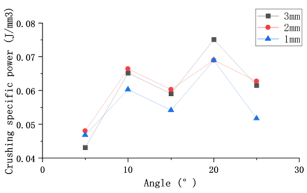


(b)Sharp round tooth

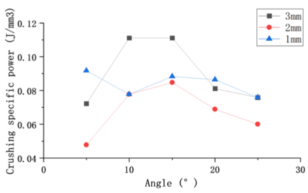


(c)Axe tooth

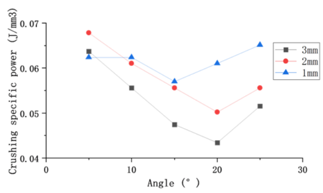
Fig 12. Crushing volume of different PDC teeth



(a)Plane tooth



(b)Sharp round tooth



(c)Axe tooth

Fig 13. crushing specific work of different PDC teeth

The simulation results of three types of PDC tooth crushing specific work are shown in Figure 13. For flat teeth: at a forward inclination angle of 5 °, the crushing specific work is the smallest at 3mm, followed by 1mm and then the largest at 2mm; At other angles, the crushing specific work is smaller at 1mm and the maximum is 3mm. As shown in the figure, for fractured sandstone, the highest rock breaking efficiency is achieved when the plane teeth have a forward inclination angle of 15 ° and a depth of 1mm. For sharp circular teeth: at a depth of 1mm, the crushing specific energy shows a trend of first decreasing, then increasing, and then decreasing. The minimum value of crushing specific energy appears at 10 °; When the depth is 2mm, the crushing specific energy shows a trend of increasing first and then decreasing, with the minimum value appearing at 5 °; When the depth is 3mm, the crushing specific energy shows a trend of increasing first and then decreasing, with the minimum value appearing at 5 °; For fractured sandstone, the highest rock breaking efficiency is achieved with sharp circular teeth at a forward inclination angle of 5 ° and a depth of 2mm. For axe shaped teeth: all three depths show a trend of decreasing and then increasing, with the minimum value appearing at 15 ° at 1mm and at 20 ° at 2-3mm; For fractured sandstone, the axe shaped teeth have the highest rock breaking efficiency at a forward inclination angle of 20 ° and a depth of 3mm. Comparing the effects of three teeth on sandstone fragmentation, the axe shaped teeth have the strongest ability to destroy sandstone.

4. Summary

In order to explore the rock breaking laws of existing non planar teeth, indoor single tooth rock breaking experiments and numerical simulation were conducted on planar teeth, pointed circular teeth, and axe shaped teeth. After research and analysis, the conclusions obtained are as follows:

(1) After indoor single tooth rock breaking experiments, it was found that for flat teeth and pointed circular teeth with a depth of 1mm, increasing the forward inclination angle of the teeth increases the crushing volume, while in other cases, the crushing volume of the teeth decreases. From the perspective of fractured volume, planar teeth have the highest volume of fractured rocks; When the rake angle of PDC teeth is increased, the cutting force of flat teeth and axe teeth decreases, while the cutting force of pointed circular teeth increases; Comparing the experimental results with the simulation results, firstly, for the trend, the experimental results are consistent with the simulation results. Secondly, through data extraction and comparison, the maximum error of the data is 9% and the minimum error is 1%. Therefore, it is considered that the analysis results are true and the analysis method is effective.

(2) During simulation analysis, it was found that increasing the depth of PDC teeth would lead to an increase in the cutting force of PDC and the volume of fractured rock. For flat teeth, the peak cutting force at three depths occurs at a rake angle of 20 °, the maximum breaking volume at a depth of 1mm occurs at 15 °, and the maximum value at the other two depths occurs at 10 °. For sharp circular teeth, the cutting force at three depths shows a trend of decreasing and then increasing, with the maximum value appearing at 5 ° and the inflection point at 20 °; The maximum volume of fractured rock at three depths of penetration occurs at a forward inclination angle of 15 °. For axe shaped teeth, at a depth of 1-2mm, the volume of fractured rock shows a gradually decreasing trend, with a peak appearing at 5 °; At a depth of 3mm, the crushing volume shows a trend of first decreasing and then increasing, with a peak at 5 ° and a turning point of 20 °.

(3) After comparing the indoor single tooth rock breaking experiment and numerical simulation results, it was found that for planar teeth, the best working condition for crushing sandstone is a forward inclination angle of 15 ° and a depth of 1mm; For sharp circular teeth, the best working condition for crushing sandstone is a forward inclination angle of 5 ° and a depth of 2mm; For axe shaped teeth, the best working condition for crushing sandstone is a forward inclination angle of 20 ° and a depth of 3mm; Comparing the crushing effects of three teeth on sandstone, the axe type has the best crushing effect.

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