Study on Rock Breaking Law of Anisotropic PDC Teeth

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Abstract

The indoor single tooth rock breaking experiment and numerical simulation of rock breaking are carried out for plane teeth, sharp round teeth and axe teeth. The effects of different penetration depth and rake angle on the rock breaking efficiency of PDC teeth are analyzed. Analyze the experimental results and simulation results: the trend of experimental results and simulation results is the same. Secondly, through the extraction and comparison of data, the maximum error of data is 9% and the minimum error is 1%, so it is considered that the analysis method is effective; 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 round teeth, and the cutting force of axe teeth is greater than that of the other two teeth; The best rock breaking conditions of plane teeth, sharp round teeth and axe teeth of broken sandstone are rake angle 15 °, depth 1mm, rake angle 5 °, depth 2mm and rake angle 20 °, depth 3mm; Comprehensively comparing the effect of three teeth in crushing sandstone, the axe type has the best crushing effect. Then the three kinds of teeth are simulated for rock breaking. It is found that the tooth distribution method of front special-shaped teeth and back plane teeth will lose the attack power of special-shaped teeth and reduce the rock breaking efficiency.

Keywords

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

1. Preamble

PDC bits are currently used with high frequency, and their performance in deep formations or some difficult formations is better than that of other bits, but compared with themselves, the rock breaking efficiency in the above formations is reduced [1-3]. Therefore, it is of great significance to study the influence law of the rock breaking efficiency of non planar teeth to improve the rock breaking efficiency of PDC bits.

Zhai Yinghu et al. [4] found that the size of the cutting load would be affected by the size of the contact area of the tooth surface, and the size of the cutting force would affect the axial force. Liang Erguo [5] found after the single tooth experiment that for non planar teeth, when the contact area of teeth is the same, the longer the arc of non planar teeth, the greater the cutting force; At the same time, the stronger the drillability of rock, the greater the cutting force. Tian Feng et al. [6] established the relationship between cutting area and crushing volume by mathematical method. Wang Jiajun et al. [7] found after the single tooth rock breaking experiment that when the penetration depth of PDC teeth is constant, the cutting force of cutting teeth will also increase with the acceleration of the rotating speed of the rotary table. Zhu Xiaohua [8] and others proved through single tooth scraping experiments that the larger the cutting angle of PDC teeth, the higher the rock breaking efficiency,

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and as the confining pressure of rock increases, the difficulty of rock breaking also increases. Hertz [9] used the elastic contact theory to study the contact between PDC teeth and rock in his research, and came to the conclusion that when the contact load of two objects reached the critical value, the rock would produce conical cracks and expand downward to form an open state. When this can explain the state of PDC eating into the rock at first. Mendoza et al. [10] found after rock experiments that when the strength of rock is high, the broken rock particles will affect the residual strength of rock. Zeuch [11] found that the change of the depth of penetration would affect the development of rock cracks when conducting the depth of penetration experiment. Gomez [12] conducted induced damage experiments on rocks. After the experiments, it was found that the application of induced loads had a great impact on the static splitting strength of rocks, and reduced their dependence on the damage direction. Glowka et al. [13] found in the process of experiments that the friction generated during cutting can significantly reduce the life of PDC teeth. Rashidi et al. [14] used ROP model to study bit selection. They added conventional drilling parameters to the model and established reliable output data for bit selection analysis. Johnson [15] developed a new type of non planar PDC cutting teeth, which can discharge rock debris through high and low surfaces when breaking rocks.

To sum up, the research on PDC teeth mostly focuses on the contact relationship between teeth and rocks, and the relationship between the contact radian and cutting area of PDC cutting teeth and rock breaking efficiency. However, applying the above cutting principles or developing a new type of cutting teeth requires a lot of energy. Compared with developing new types of teeth, few people study the rock breaking efficiency of existing tooth shapes. Therefore, this paper takes three kinds of PDC teeth as research objects to explore their rock breaking laws and provide ideas for the subsequent tooth layout of PDC bits.

2. Indoor Single Tooth Rock Breaking Test

2.1 Experimental Establishment

During drilling and rock breaking, the bit rotates and axially moves around the center line of the drill string, while the PDC teeth rotate around the center line of the drilling direction. Because the depth of the PDC bit into the formation is very shallow, the penetration depth of a single PDC tooth into the formation is basically the same after one revolution. In the single tooth experiment, the movement process of PDC teeth is simplified to a straight cutting movement with a fixed depth, as shown in Fig. 1. The rock used in the experiment is wusheng sandstone, and the tooth shapes are plane teeth, pointed round teeth and axe teeth. The experimental equipment, rock and cutting teeth used in the experiment are shown in Fig. 2.

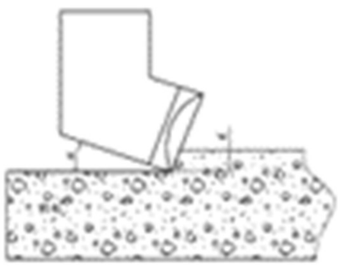

Fig. 1 simplified model of PDC tooth rock interaction

Fig. 2 single tooth rock breaking equipment and rock

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In the process of rock breaking, PDC teeth are mainly subjected to the tangential force opposite to the moving direction of the cutting teeth and the axial force along the drill axis.

Crushing specific work refers to the energy consumed for crushing unit volume of rock. The smaller the value, the lowest the energy required for crushing unit volume of rock by this tool or method. Therefore, the crushing specific work is used to evaluate the rock breaking effect of teeth. The calculation formula is as follows (1), Where: MSE_r is the actual crushing specific work; W is energy required for rock breaking; V_r is the true crushing volume.

$$MSE_r = \frac{W}{V_r} \tag{1}$$

2.2 Analysis of Experimental Results

The experimental conditions are that the rake angle is 10 °, 15 °, and the penetration depth is controlled at 1mm and 1.5mm, as shown in Fig. 3. The tangential force (cutting force), axial force (weight on bit) and the volume of broken rock of the experimental teeth are extracted, and the specific work of breaking is calculated by using the collected rock volume according to formula (1).

The cutting diagram of the three kinds of teeth when breaking rock extracted from the experimental data is shown in Fig. 5. It can be seen from the figure that the cutting force of each tooth increases with the increase of the penetration depth. When the rake angle of PDC teeth is increased, the cutting force of plane teeth and axe teeth is reduced, while the cutting force of pointed round teeth is increased, which means that increasing the rake angle of pointed round teeth will increase the energy of breaking rocks.

Fig. 3 rock breaking pictures of three kinds of teeth

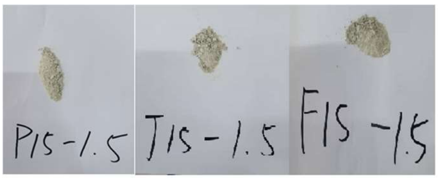
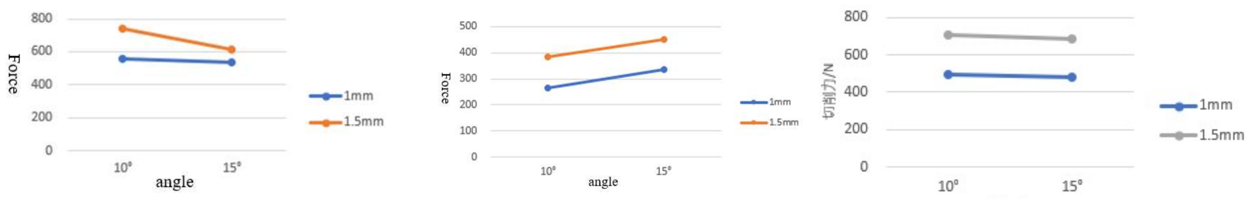


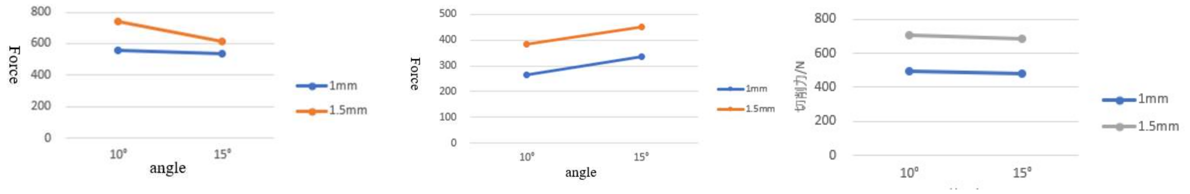
Fig. 4 rock cuttings broken by three kinds of teeth



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

Fig. 5 cutting force of different PDC teeth

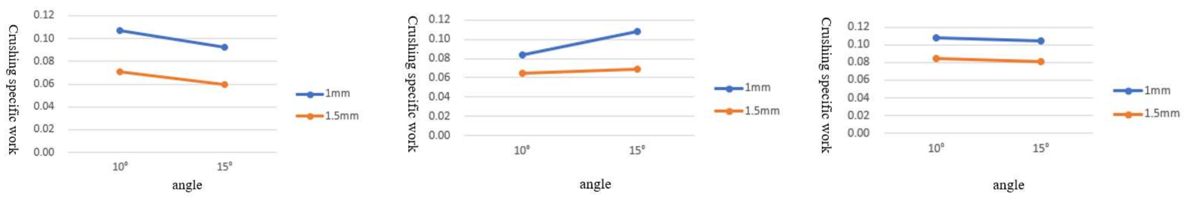
The broken rock volume when the three teeth break rock is shown in Fig. 6. Increasing the penetration depth of PDC teeth will lead to an increase in the broken volume of PDC teeth. For plane teeth and pointed round teeth with a depth of 1mm, the crushing volume increases with the increase of the rake angle of the teeth, and decreases in other cases. From the level of crushing volume, the volume of rock crushed by plane teeth is the largest.



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

Fig. 6 broken rock volume of different PDC teeth

The crushing specific work of the three teeth when breaking rock is shown in Fig. 7. Increasing the penetration depth will reduce the crushing specific work of the teeth; In addition to the pointed round teeth, increasing the rake angle of the teeth will reduce the crushing specific work of the teeth, that is, the rock breaking efficiency will increase. From the horizontal point of view, the crushing efficiency of the sharp round teeth is the highest, that is, for the fractured sandstone, the sharp round teeth are the most suitable.



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

Fig. 7 crushing specific work of different PDC teeth

3. Finite Element Analysis Model

3.1 Modeling

According to Saint Venant's theorem and considering the computing power of the computer, the size of the rock model is set as $80mm \times 50mm \times 25mm$, Because the purpose of the analysis is the benchmarking experiment, the rock model parameters are wusheng sandstone, and the PDC teeth used are plane teeth, ridge teeth and pointed round teeth. The diameter of each tooth is 15.88mm and the height is 13.2mm.

In order to better benchmark the experiment, the simulation is 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) Ignoring the influence of rock cuttings on the subsequent cutting process; The finite element model established according to the rock breaking experiment is shown in the figure:

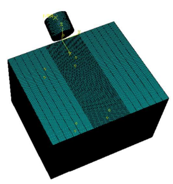


Fig. 8 finite element analysis model

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In the analysis model, c3d8r grid is used for both rock and tooth grids, and grid refinement is carried out in the area where the rock is scraped. The global grid density is 5, and the refined grid density is 0.5.

3.2 Rock Breaking Analysis Results of

In the analysis, the two parameters of the tooth are also considered to be changed, namely, the rake angle and the penetration depth of the tooth. The rake angle is 5 °, 10 °, 15 °, 20 ° and 25 °, and the penetration depth is 1mm, 2mm and 3mm. In the actual single tooth rock breaking experiment, the scraping distance of PDC teeth was 300mm, while in the process of numerical simulation of PDC teeth, the actual scraping distance was 50mm due to the limitation of computer computing capacity. Therefore, in order to verify the accuracy of the analysis results, we extracted the cutting force value at 1mm depth for comparison, as shown in FIG. 9. First of all, for the trend, the trend of the experimental results is the same as that of the simulation results. 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 cutting force simulation results of the three PDC teeth are shown in FIG. 10. Increasing the penetration depth of planar teeth will lead to the overall increase of cutting force; When the rake angle is 10 ° and 20 °, the cutting force of planar teeth reaches two peaks, and after the peak, the cutting force decreases. Sharp round teeth are the same as plane teeth, and increasing the penetration depth will lead to an overall increase in cutting force. When the rake angle of the pointed circular teeth is 5 ° ~ 20 °, the cutting force decreases, and rises slightly at 25 °. Increasing the depth of the axe shaped teeth will also improve the cutting force of the teeth as a whole. After changing the rake angle of the axe teeth, it is found that the peak value of the cutting force of the axe teeth appears at 15 °, and then decreases on both sides. By comprehensively comparing the cutting forces of the three teeth, it is found that the cutting forces of the axe teeth are greater than those of the other two teeth at three different depths, and the axe teeth are more aggressive.

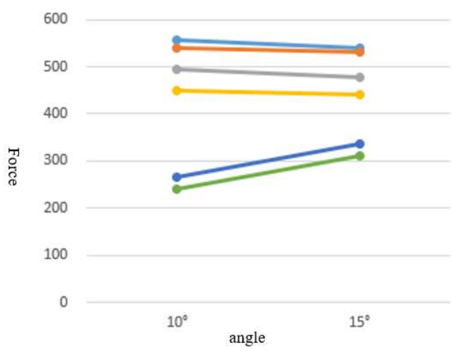
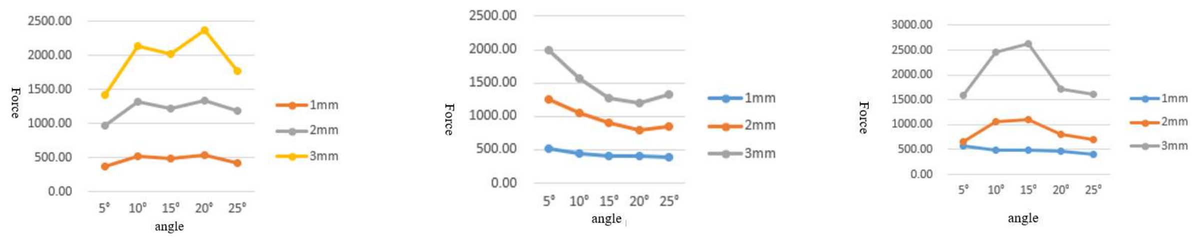


Fig. 9 comparison between experimental results and simulation results

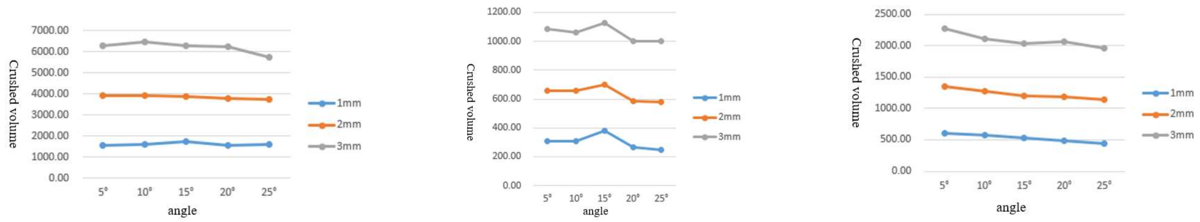
The simulation results of the crushing volume of the three PDC teeth are shown in FIG. 14. For the three kinds of teeth, increasing the depth will lead to an increase in the volume of the broken rock of the three kinds of teeth. For plane teeth, the volume of fractured rock increases with the increase of rake angle at the depth of 2mm and 3mm, and the peak appears at 5 ° at 2mm and 10 ° at 3mm. However, for a 1 mm depth, the maximum volume of broken rock appears at 15 °. For sharp round teeth, the change of the whole broken rock volume presents a triangle when the rake angle is increased, and the maximum value of the broken rock volume appears at 15 ° at three draughts. For axe teeth, when the rake angle increases, the change of the whole broken rock volume shows a decreasing trend, and the maximum value of the broken rock volume appears at 5 ° at three draughts. Through comprehensive comparison of the three teeth, it is found that under the same conditions, the volume of rock broken by plane teeth is larger than that of axe teeth and pointed round teeth.

The specific work simulation results of the three PDC teeth are shown in FIG. 15. For plane teeth, at 5 ° rake angle, the crushing specific work at 3mm is the smallest, 1mm is the second, and 2mm is the largest; In other angles, the crushing specific work is smaller when it is 1mm and the crushing specific work is largest when it is 3mm. It can be seen from the figure that for broken sandstone, the rock breaking efficiency is the highest when the rake angle of plane teeth is 15 ° and the depth of draught is 1mm. For sharp round teeth, when the depth is 1mm, the crushing specific work tends to decrease first, then increase and then decrease, and the minimum value of crushing specific work appears at 10 °; When the draught is 2mm, the crushing specific work increases first and then decreases, and the minimum value appears at 5 °; When the draught is 3mm, the crushing specific work increases first and then decreases, and the minimum value appears at 5 °; For broken sandstone, the rock breaking efficiency is the highest when the rake angle is 5 ° and the depth is 2mm. For axe shaped teeth, the phase decreases and then increases at three draughts. The minimum value appears at 15 ° at 1mm and 20 ° at 2 ~ 3mm; For broken sandstone, the axe shaped teeth have the highest rock breaking efficiency when the rake angle is 20 ° and the depth is 3mm. By comprehensively comparing the effects of three teeth in crushing sandstone, axe teeth have the strongest ability to destroy sandstone.



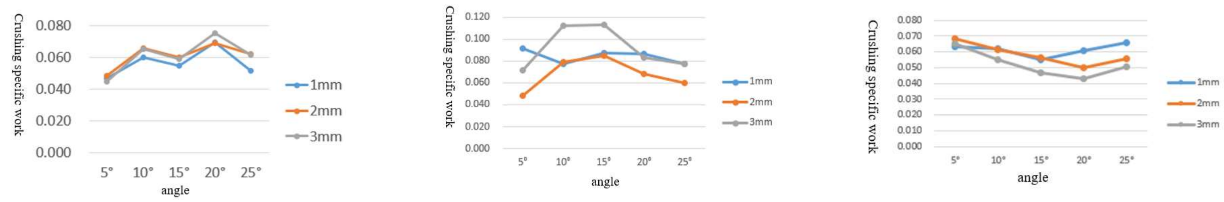
(a) Plane tooth (b) Pointed round tooth (c) Axe tooth

Fig. 10 cutting force of different PDC teeth



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

Fig. 11 crushing volume of different PDC teeth



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

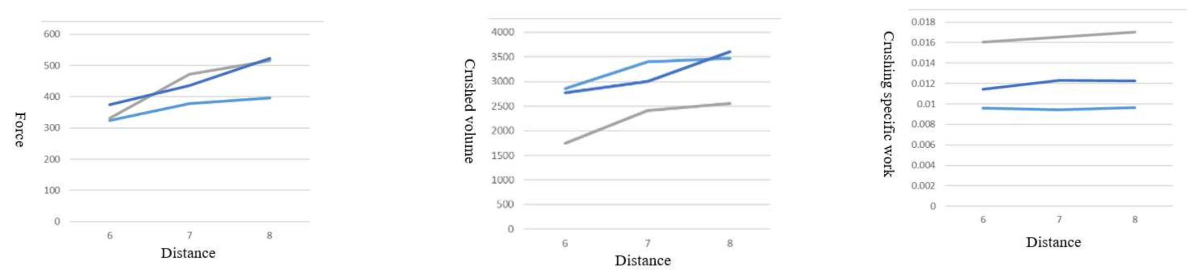
Fig. 12 crushing specific work of different PDC teeth

3.3 Combined Rock Breaking Analysis Results

When PDC bit arranges teeth, it will combine planar teeth and special-shaped teeth to arrange teeth. In order to explore the rock breaking effect of actual mixed teeth, the rock breaking simulation analysis of planar teeth + pointed circular teeth and planar teeth + axe teeth combination is carried out. During the analysis, the simulated teeth are front and rear teeth, the front row is special-shaped teeth, and the rear row is planar teeth; According to the rock breaking results of the teeth, it is determined that the rake angle of all teeth is 20 °, the tooth depth of the front row is 1mm, and the tooth depth of the rear row is 2mm. The influence of the spacing of the front row teeth of 6, 7, and 8mm on the rock breaking effect is explored. The simulation model is shown in FIG. 13. The analysis results are shown in FIG. 14.

Fig. 13 full plane tooth rock breaking model

From the analysis results, it can be seen that when the full plane teeth break rock, the cutting force of the rear plane teeth also increases with the increase of the front tooth pitch, but it is still smaller than that when the single plane teeth scrape. With the increase of the tooth pitch at the front end, the volume of broken rock at the back end plane teeth also increases; With the increase of the front-end tooth pitch, the crushing specific work of the rear-end plane teeth develops in a V-shape; When plane teeth + pointed round teeth are used, the cutting force of the back-end plane teeth is also increased with the increase of the front-end tooth pitch, but it is still smaller than that of the single plane tooth scraping. With the increase of the tooth pitch at the front end, the volume of broken rock at the back end plane teeth also increases; With the increase of the front-end tooth pitch, the crushing specific work of the rear-end plane teeth tends to increase; With the increase of the front-end tooth pitch, the cutting force of the rear-end plane teeth is also increasing, but it is still smaller than that of the single plane teeth when scraping. With the increase of the tooth pitch at the front end, the volume of broken rock at the back end plane teeth also increases; With the increase of the front-end tooth pitch, the crushing specific work of the back-end plane teeth develops in an inverted V shape.



(a) cutting force (b) Crushing volume (c) Crushing specific work

Fig.14 analysis results of combined rock breaking

4. Conclusion

In order to explore the rock breaking law of existing non planar teeth, this paper carries out indoor single tooth rock breaking experiments and combined rock breaking numerical simulation for planar teeth, pointed circular teeth and axe shaped teeth. After research and analysis, the conclusions are as follows:

(1) Through the indoor single tooth rock breaking experiment, it is found that for the plane teeth and pointed round teeth with a depth of 1mm, the crushing volume increases with the increase of the rake angle of the teeth, and decreases in other cases. From the level of broken volume, the volume of rock broken by plane teeth is the largest; When the rake angle of PDC teeth is increased, the cutting force of plane teeth and axe teeth is decreased, but the cutting force of pointed round teeth is increased;

Compare the experimental results with the simulation results. Firstly, the trend of the experimental results is the same as that of the simulation results. 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 results are true and the analysis method is effective.

(2) During the simulation analysis, it is found that increasing the penetration depth of PDC teeth will lead to an increase in the cutting force of PDC and the volume of broken rock. For plane teeth, the peak value of cutting force at three draughts occurs at 20 °, the maximum value of crushing volume at 1mm draught occurs at 15 °, and the maximum value at the other two draughts occurs at 10 °. For pointed round teeth, the cutting force at three depths of draft is decreasing and then increasing, with the maximum value at 5 ° and the inflection point at 20 °; The maximum values of the volume of broken rock under the three depths of draught all occur at 15 ° forward inclination. For axe shaped teeth, the volume of broken rock gradually decreases at a depth of 1 ~ 2mm, and the peak appears at 5 °; At a depth of 3mm, the crushing volume tends to decrease first and then increase, with a peak value of 5 ° and an inflection point of 20 °.

(3) After comparing the indoor single tooth rock breaking experiment and numerical simulation results, it is found that the best working condition for the plane tooth to break sandstone is 15 ° forward inclination and 1mm deep draft; For sharp round teeth, the best working condition for broken sandstone is 5 ° forward inclination and 2mm deep draft; For axe teeth, the best working condition for broken sandstone is 20 ° forward inclination and 3mm deep draft; Comprehensively comparing the effects of three teeth on sandstone crushing, the axe type has the best crushing effect.

(4) Through the rock breaking simulation analysis of different tooth combinations, it is found that under the arrangement mode of special-shaped teeth in the front row and plane teeth in the back row, the crushing efficiency of plane teeth is the highest at three spacings, but this arrangement of teeth will lose the attack force of PDC special-shaped teeth, so pay attention to it when arranging teeth.

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