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Study on the Efficiency of Cutting Granite with Ridge Teeth

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Abstract

In order to explore the crushing effect of roof teeth on granite in Qinghai Oilfield, the rock breaking efficiency of roof teeth was studied. Through the indoor single tooth rock breaking experiment, rock mechanics parameter experiment and numerical simulation of the rock breaking process of roof teeth, the influence of cutting parameters (depth and rake angle) of roof teeth and tooth arrangement mode on the rock breaking efficiency of roof teeth is judged. Through analysis, the best cutting parameters of plane teeth are 5 °, 3mm; The best cutting parameter of ridge teeth is 5 °, 2mm deep, and the rock breaking effect of ridge teeth is better than that of plane teeth.

Keywords

Ridge Tooth; PDC Tooth Rock Breaking Test; Numerical Simulation; Cutting Parameters; Tooth Distribution Parameters.

1. Preface

PDC bits are currently used more frequently, and their performance in deep formations or some difficult to drill formations is superior to other bits. However, compared with its own, the rock breaking efficiency in the above formations is reduced, so studying the impact of PDC teeth on rock breaking efficiency is of great significance for improving the rock breaking efficiency of PDC bits.

The research on PDC teeth mainly focuses on the contact relationship between teeth and rock, as well as the relationship between the contact arc and cutting area of PDC teeth and rock breaking efficiency. However, using the above cutting principles to develop a new type of cutting tooth requires a lot of manpower, material resources, and time. Compared to developing new types of teeth, studying the rock breaking efficiency of several existing tooth shapes can save costs. Therefore, this article takes the existing commonly used roof teeth as the research object to study a rock breaking law of the existing teeth, providing ideas for the subsequent placement of PDC drill teeth.

2. Experiment on Rock Mechanical Parameters

In order to accurately obtain the rock information of Qinghai Oilfield and establish an accurate numerical simulation model, rocks from the Yuedong Structure in the Qaidam Basin of Qinghai Oilfield were collected for rock mechanics experiments. The main contents of the experiments were rock triaxial compressive strength experiments and rock full stress strain experiments. The triaxial compressive strength, elastic modulus, Poisson's ratio, and rock full stress strain curves of the rocks were obtained. The experimental instruments and rocks are shown in Figure 1. After the experiment, the elastic modulus of Yuedong structural rock was 29310MPa, the compressive strength was 288.2MPa, and the Poisson's ratio was 0.38. The complete stress-strain curve is shown in Figure 2.

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Figure 1. Rock Mechanics Experiment Equipment and Experimental Rock Samples

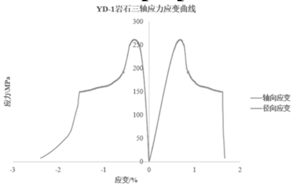


Figure 2. Total Stress Strain Curve of Rock

3. PDC Tooth Rock Breaking Experiment

3.1. Experimental Setup

During the drilling process, the movement trajectory of PDC teeth is limited by the drill bit body and represents a circular motion at a fixed depth. Therefore, in the experiment, it is simplified to a linear motion at a fixed depth. During the experiment, a three-dimensional force sensor is used to collect axial and tangential forces. The simplified diagram of the experimental principle and the experimental instrument are shown in Figures 3-4. The evaluation of experimental results takes the form of mechanical specific work, that is, the energy consumed by crushing a unit volume of rock. The calculation formula is:

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

Where: MSE_r is the actual crushing specific work; W is the energy required for rock breaking; V_r Is the true broken volume.

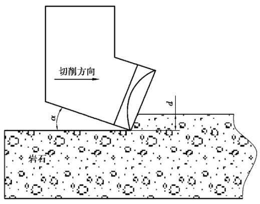
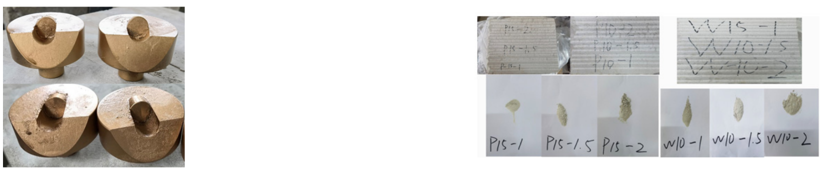


Figure 3. Simplified diagram of experimental principle

Figure 4. Experimental Equipment Diagram

3.2. Experimental Result



(a)Experimental tooth (b)Experimental rock cuttings

Figure 5. Experimental Process Diagram

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The experimental tooth shapes are planar teeth and ridge teeth. The experimental cutting conditions are 10 ° and 15 ° rake angles, and the bite depth is controlled to be 1mm, 1.5mm, and 2mm. The experimental process is shown in Figure 5. The experimental results are shown in Table 1

Table 1. Indoor Single Tooth Rock Breaking Test Results

Jugged	Front inclination angle /°	Cutting depth /mm	Average cutting force /N	Crushed volume /mm³	Crushing specific work / J/mm³
Planar tooth	10	1	557	1475	0.11
		1.5	737	2955	0.07
		2	944	4563	0.06
	15	1	539	1664	0.092
		1.5	612	2903	0.06
		2	798	3847	0.058
Ridge tooth	10	1	563	1679	0.095
		1.5	704	2490	0.080
		2	935	4334	0.061
	15	1	447	886	0.095
		1.5	655	1857	0.068
		2	900	2928	0.062

According to the analysis of experimental results, when the plane tooth is at a depth of 15 ° and 2 mm, the rock fragmentation effect of the Yuedong structure is the best; When the roof ridge teeth are at a depth of 10 ° and 2 mm, the rock fragmentation effect of the Yuedong structure is the best; The rock breaking effect of ridge teeth is better than that of planar teeth. However, it is not yet known whether these are the optimal rock breaking parameters for the two types of teeth, so it is necessary to conduct rock breaking process simulation to explore the optimal rock breaking parameters.

4. Numerical Simulation Model of PDC Tooth Rock Breaking Process

4.1. Simulation Model Establishment

According to Saint Venant's theorem, considering the computing power of the computer, the rock model size is set to $100\text{mm} \times 50\text{mm} \times 25\text{mm}$, and the material parameters of the rock are obtained through indoor rock experiments. During the simulation, the following assumptions were made: the rock is isotropic regardless of temperature; Ignore the impact of rock debris on the cutting process. In the analytical model, C3D8R meshes are 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. The established finite element model is shown in Figure 6.

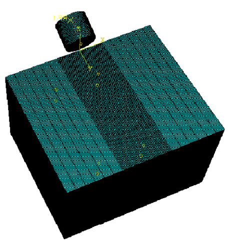

Figure 6. Finite Element Analysis Model

The Drucker—Prager yield criterion is selected as the strength criterion for rock, which considers the confining pressure and the expansibility of the rock, and its calculation formula is:

$$F = t - p\tan\beta - d = 0 \tag{2}$$

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

Where: β is the internal friction angle of the material; d is the cohesive force of the material; K is the ratio of tensile test yield stress to compressive test yield stress.

The damage criterion for rock adopts the shear damage rule, whose principle is that at the initial stage of rock failure, the equivalent plastic strain is $\bar{\varepsilon}_s^{pl}$,which is a function related to the shear stress rate θ_s and the plastic strain rate $\dot{\bar{\varepsilon}}^{pl}$, so:

$$\theta_s = \left(q + k_s p\right)/\tau_{\max} \tag{4}$$

Where: is the maximum shear stress; Is a material parameter.

When rock begins to fail:

$$\omega_s = \int \frac{d\bar{\varepsilon}_s^{pl}}{\bar{\varepsilon}_s^{pl}} = 1 \tag{5}$$

Where: ω_s is a state variable. When the rock reaches a failure state, the failure process of the rock is shown by the complete stress-strain curve of the rock

In the single tooth rock breaking experiment, the scraping distance of the PDC teeth is larger than the simulation value, so the calculation of the crushing volume and the crushing specific work in the numerical simulation analysis are both smaller than the experimental values. Therefore, in order to verify the accuracy of the analysis results, the cutting force values at a depth of 1mm are extracted for comparison. As shown in Table 2, through calculation, the maximum error is 7.42%, and the average error is stable at about 5%. Therefore, the analysis model method is considered effective.

Table 2. Comparison between indoor single tooth rock breaking experiment and numerical simulation analysis results

Jugged	Cutting depth /mm	Front inclination angle /°	Simulate cutting forces /N	Experimental cutting force /N	error /%
Planar tooth	1	10	526.15	557	5.54
		15	499	539	7.42
Ridge tooth	1	10	530.22	563	5.01
		15	437.96	447	4.93

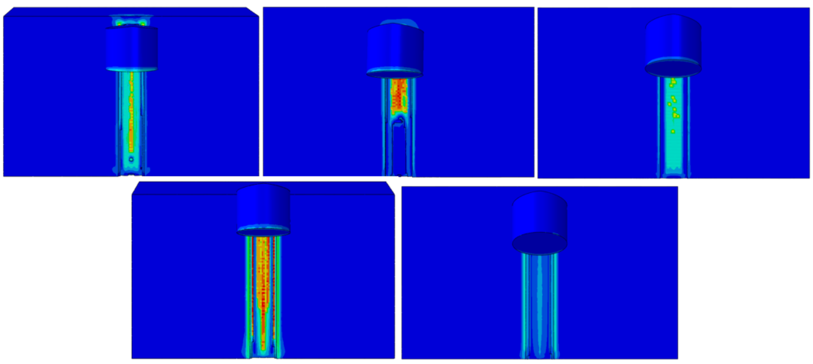

Figure 7. Analysis Results of 1mm Depth of Roof Ridge Teeth

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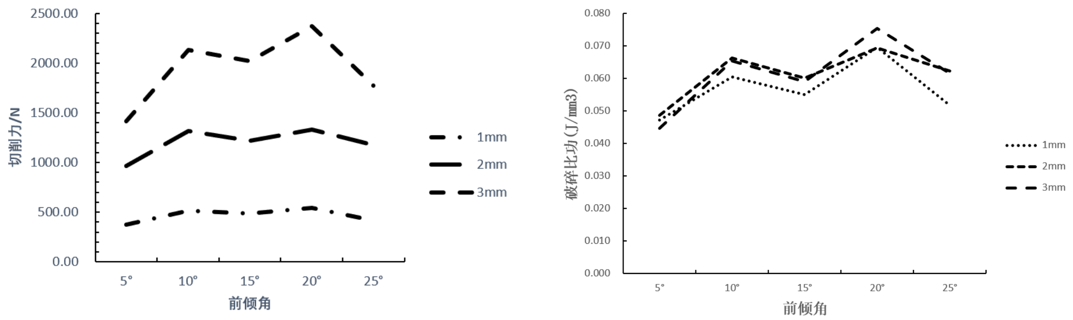
4.2. Cutting Parameters

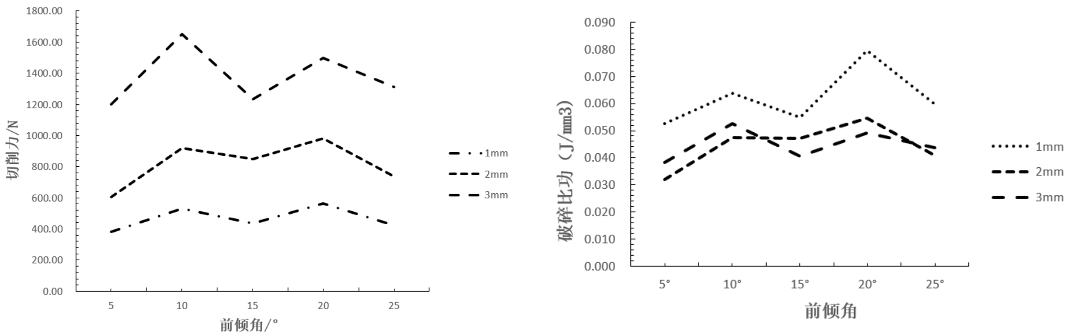
In order to explore better cutting conditions for the two types of teeth, during numerical simulation, the rake angles are set at 5 °, 10 °, 15 °, 20 °, and 25 °, and the feed depths are 1mm, 2mm, and 3mm. The results of plane tooth cutting force and crushing specific work are shown in Figure 8, and the results of ridge tooth are shown in Figure 9.



(a)Cutting force (b)Crushing specific work

Figure 8. Numerical analysis results of planar teeth

As can be seen from Figure 8, for the cutting force, increasing the depth of the planar tooth will significantly increase the cutting force. Under each depth of the tooth, the cutting force at each angle assumes an M-shaped distribution (20 °>10 °>15 °>25 °>5 °); The distribution of crushing specific work at each depth is also a M-like distribution (20 °>10 °>15 °>25 °>5 °). From the graph, it can be seen that for planar teeth, a depth of 5 °, 3mm is the best cutting parameter.



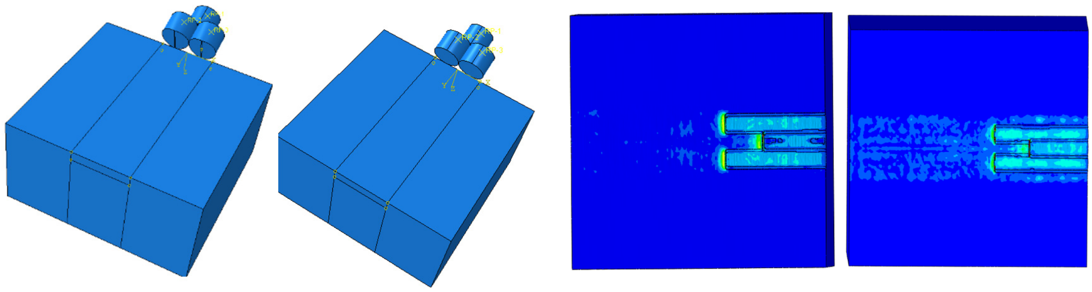
(a)Cutting force (b)Crushing specific work

Figure 9. Numerical Analysis Results of Ridge Teeth

As can be seen from Figure 9, for the cutting force, increasing the depth of the ridge tooth will significantly increase the cutting force. Under each depth of the tooth, the cutting force at each angle assumes an M-shaped distribution; The distribution of crushing specific work at each depth is also a M-like distribution. From the graph, it can be seen that for ridge teeth, the optimal cutting parameters are at a depth of 5 ° and 2mm.

4.3. Mixed Cutting Parameters

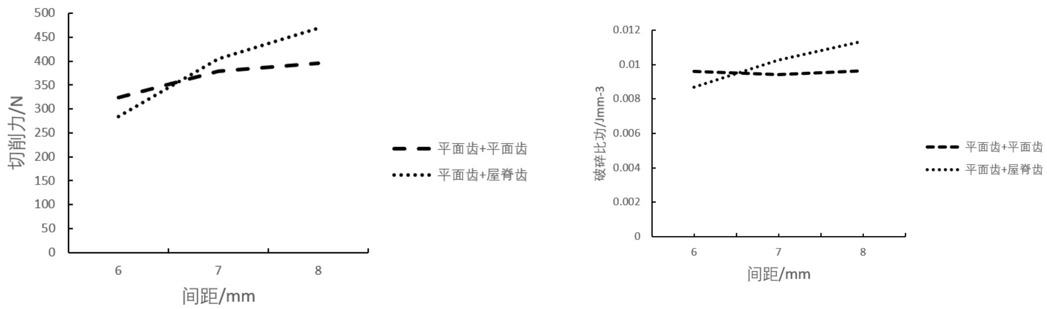
The simulation environment is set as follows: the PDC tooth rake angle is set to 20 °; The experimental depth is set to 1mm for the front row that first contacts the rock, and 2mm for the rear row teeth. The tooth spacing is set to 6mm, 7mm, and 8mm, and the simulation model is shown in Figure 10.



(a)Analysis model (b)Scraped rock

Figure 10. Hybrid Cutting Analysis Model

As can be seen from Figure 11, increasing the spacing of the rear teeth will increase the cutting force required for rock breaking; In terms of the energy required for rock breaking, a tooth spacing of 6 mm or less can increase the efficiency of rock breaking. Compared with single tooth rock breaking, mixed tooth energy significantly reduces the cutting force and energy required for rock breaking



(a)Cutting force (b)Crushing specific work

Figure 11. Numerical Analysis Results of Mixed Rock Breaking

5. Conclusion

(1) Using numerical simulation software, a numerical analysis model for PDC tooth single tooth rock breaking and mixed rock breaking was established. Compared with indoor single tooth rock breaking experiments, the maximum error of the data was 7.42, and the average error was about 5%, proving that the numerical analysis method was effective;

(2) For planar teeth and ridge teeth, with the increase of the rake angle, the cutting force required for PDC teeth to break rock and the energy required for breaking rock all exhibit an M-like distribution, with the optimal cutting parameters for planar teeth being 5 °, 3mm; The optimal cutting parameter for the ridge tooth is 5 °, with a 2mm depth, and the rock breaking effect of the ridge tooth is better than that of the planar tooth;

(3) Mixing planar teeth and ridge teeth for rock breaking can effectively reduce the cutting force on each tooth and the energy required for rock breaking. When designing the tooth spacing, it is recommended to be less than 6mm.

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