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Research on the Rock-breaking Characteristics of PDC Cutting Tooth under Combined Axial and Torsional Impact

Zebing Wu, Zihao Zhang *

School of Mechanical Engineering, Xi'an Shiyou University, Xi'an Shaanxi, 710065, China

* Corresponding author: Zihao Zhang

Abstract

Aiming at the problems of low rock-breaking efficiency in hard formation and low service life of PDC bits caused by stick-slip vibration of drilling tools, in order to further study the rock-breaking characteristics of PDC cutting teeth and improve their rock-breaking efficiency, based on elastoplastic mechanics and Drucker-Prager rock failure criteria, The ABAQUS/Explicit module was used to establish the interaction model between PDC cutting teeth and rocks under the combined impact of axial torsion. The differences between conventional teeth and axe-shaped teeth in terms of displacement, cutting force, and rock damage history under the combined impact of axial torsion and conventional rock breaking were analyzed, as well as the optimal ratio of different axial torsion impact parameters corresponding to different tooth shapes. The research results show that compared with conventional rock breaking, under the combined impact of axial torsion, the cutting teeth of PDC will have a deeper rock breaking depth, the cutting force will be further reduced, and the time from damage initiation to stripping of the rock unit is less than that of conventional rock breaking. The conventional teeth have the largest rock-breaking volume when the impact amplitude is 4:1 and the impact frequency is 4:1, and the mechanical specific energy is the smallest when the impact amplitude is 4:1 and the impact frequency is 4:1. The volume of rock broken by the axe-shaped teeth is the largest when the impact amplitude is 4:1 and the impact frequency is 4:1. The mechanical specific energy is the smallest when the impact amplitude is 4:1 and the impact frequency is 3:1. It can also be concluded that axe-shaped teeth are more aggressive in rock breaking compared to conventional teeth, and their rock breaking efficiency is higher than that of ordinary teeth. The research results have certain value for improving cutting structure performance and its efficiency of rock crushing.

Keywords

Axial Torsion Combined Impact Rock Breaking; PDC Cutting Teeth; Impact Amplitude; Impact Frequency; Rock-breaking Characteristics.

1. Introduction

With the extensive development of oil and gas exploration and development projects, deep formations have gradually become a crucial growth point for improving oil and gas production efficiency. However, deep formations present a series of challenges, such as high rock hardness, strong abrasion resistance, and poor drillability [1]. When a drill bit penetrates hard formations, the cutting resistance increases significantly as the cutting depth increases. The drill bit is prone to the phenomenon of cyclic accumulation and release of torque—known as stick-slip vibration—due to insufficient cutting force. This ultimately leads to a reduction in drilling speed and a shortened service life of the drill bit [2].

Conventional drilling can no longer meet the current production requirements for deep or ultra-deep wells. In recent years, therefore, based on the one-way impact-assisted drilling technology, axial-torsional composite impact drilling technology has been developed. Axial and torsional impact forces play distinct roles in the rock-breaking process of PDC (Polycrystalline Diamond Compact) drill bits: axial impact primarily addresses the low rock-breaking efficiency caused by the small cutting depth of the drill bit's cutting teeth, while torsional impact serves to reduce the stick-slip vibration of the drill bit [3]. As an efficient rock-breaking method, axial-torsional composite impact rock-breaking is gradually emerging as a key technology for deep resource drilling. It can enhance the cutting force of the drill bit to rapidly cut and break rocks, weaken or eliminate stick-slip vibration, increase the drilling speed of the drill bit, and thereby improve the efficiency of oil and gas production [4].

It is well-known that the research on axial-torsional composite impact rock-breaking of PDC drill bits is closely related to its impact parameters. Consequently, numerous scholars at home and abroad have conducted studies on composite impact parameters. In 2014, Li Hai et al[5]. carried out a numerical simulation study on rock-breaking by PDC cutting teeth under torsional impact. In 2017, Yan Yan et al[6]. conducted an experimental study on the rock-breaking efficiency of PDC drill bits under composite conditions. In 2019, Li Yumei et al[7]. performed a simulation study on the matching characteristics of composite impact frequencies. In 2020, Liu Weiji et al[8]. investigated the rock-breaking mechanism of single-tooth composite impact cutting and compared it with that of torsional impact. In 2023, Liu Wei et al[9]. analyzed the penetration depth and rock-breaking mechanism of PDC cutting teeth under different impact drilling methods. In 2021, Karpov V. N. et al[10]. determined the high-efficiency rotary impact drilling technology for hard rocks and proposed calculation formulas for the drilling process. Also in 2021, Hu Sicheng et al[11]. analyzed the rock-breaking process and efficiency of conical teeth under rotary impact and torsional impact, and proposed that the rock-breaking process of conical teeth under both rotary and torsional impacts consists of four stages: cutting tooth penetration into rock, initiation of rock damage and through-cracks, propagation of rock damage and through-cracks, and rock collapse due to crack penetration. In 2024, Hashiba K et al[12]. published a review of theoretical, experimental, and numerical studies on rotary impact rock drilling, indicating that stress wave propagation and dynamic penetration of the drill bit are important factors affecting drilling efficiency and rate during rotary impact rock drilling. Yan Yan et al[13]. conducted a numerical simulation of the rotary impact rock-breaking process of full-scale PDC drill bits. Their analysis showed that rock damage in conventional rock-breaking mainly occurs at the bottom and front of the teeth, while rock damage in rotary impact rock-breaking occurs primarily at the bottom, front, and periphery of the teeth.

Based on the aforementioned studies, previous research has mainly focused on the design, manufacturing, and application of different types of impact drilling tools, as well as the rock-breaking effect of conventional PDC drill bits under impact. However, there is limited research on the rock-breaking process of PDC teeth with different shapes under axial-torsional composite impact. This gap hinders the selection of PDC cutting teeth under different working conditions and makes it difficult to maximize the advantages of PDC drill bits in improving drilling energy efficiency. To address this issue, it is essential to conduct numerical simulations of impact rock-breaking for PDC cutting teeth with different shapes. First, under the same parameter conditions, the rock-breaking effects of different tooth shapes should be compared, with a focus on analyzing indicators such as maximum stress, rock breaking volume, cutting force, and rock damage evolution during the rock-breaking process, so as to clarify the advantages of impact rock-breaking over conventional rock-breaking. Second, a systematic study should be conducted on the influence of different parameters (including variables such as impact load, impact frequency, and amplitude) on the rock-breaking efficiency of PDC cutting teeth, and the variation laws of rock breaking volume and mechanical specific energy of different tooth shapes with parameter changes should be observed. Furthermore, the matching mechanism between different tooth shapes and impact parameters should be identified, with

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the aim of providing theoretical and engineering references for the axial-torsional composite impact drilling process.

2. Mechanical Model of PDC Tooth Cutting

Axial-torsional composite impact drilling technology is based on traditional rotary drilling. It applies a high-frequency impact force in the axial direction of the drill bit and, at the same time, exerts a time-varying torque in the torsional direction of the drill bit. This enables the drill bit to impact the rock periodically in the axial direction while performing torsional cutting in the circumferential direction, converting the uniform-speed rock-breaking in traditional drilling into hammering-like rock-breaking [14]. As shown in Figure 1, it is a schematic diagram of the cutting process of a single tooth under pressure. In the plane strain space, a static coordinate system XOY is assumed, and the cutting process is continuous. The overall movement of the cutting tooth combines the axial up-and-down impact movement and the torsional forward-backward impact movement.

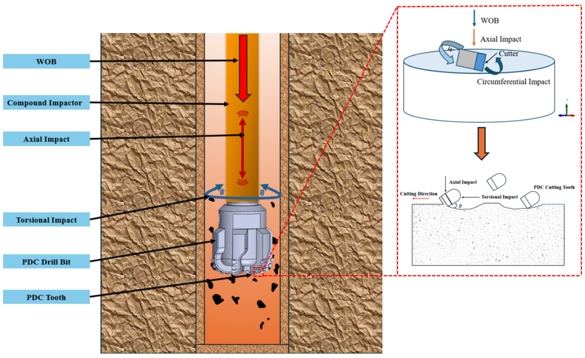


Figure 1. Rock breaking mechanical model of PDC cutting teeth

3. Establishment of Rock-Breaking Model

3.1. Rock Constitutive Model

Rock is a material with nonlinear and anisotropic structure. Therefore, selecting an appropriate rock constitutive model is a prerequisite for establishing a rock-breaking model. A rock constitutive model is a mathematical framework that describes the stress-strain relationship of the material; based on experimental data and theoretical assumptions, it enables the predictive simulation of the yield and failure behavior of rock under multiaxial stress conditions. The traditional Mohr-Coulomb (M-C) criterion adopts a linear function. Although it is widely used in two-dimensional stress analysis, it has the limitation of not considering the intermediate principal stress effect, which easily leads to deviations in the prediction of rock strength under high confining pressure. The Drucker-Prager (D-P) criterion constructs a nonlinear yield function by introducing the hydrostatic pressure correction term (I_1) and the deviatoric stress invariant (J_2). It not only retains the shear failure mechanism of the M-C criterion but also achieves a refined description of the three-dimensional stress state through the σ sensitivity parameter. The improvements of the D-P criterion over the M-C and Mises criteria are as follows [15]:

$$\rho I_1 + \sqrt{J_2} - K = 0 \tag{1}$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \tag{2}$$

$$J_2 = \frac{1}{6}\left[(\sigma_1 + \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \tag{3}$$

$$\alpha = \frac{2\sin\beta}{\sqrt{3}\left(3-\sin\beta\right)} \tag{4}$$

$$K = \frac{6e\cos\beta}{\sqrt{3}\left(3-\sin\beta\right)} \tag{5}$$

Where: I_1 is the first invariant of stress; J_2 is the second invariant of the stress deviator; α and k are experimental constants related only to the internal friction angle β and cohesion e of the rock; σ_1, σ_2, σ_3 are the first, second, and third principal stresses, respectively.

PDC teeth mainly break rock through a shearing mechanism. Rock damage begins to occur when the plastic stress of the rock exceeds its critical value. Ignoring the influence of damaged elements on the rock, the plastic strain criterion for the rock is as follows:

$$\varepsilon^{r} \le \varepsilon_f^{rl} \tag{6}$$

Where: ε^{r} is the equivalent plastic strain of the rock, ε_f^{rl} is the equivalent plastic strain of the rock when failure occurs.

3.2. Material Properties and Boundary Conditions

The material parameters of the PDC cutting teeth are as follows: elastic modulus of 890 GPa, Poisson's ratio of 0.077, and density of 3520 kg/m^3; the material parameters of the rock are as follows: density of 2260 kg/m^3, elastic modulus of 27 GPa, Poisson's ratio of 0.15, dilatancy angle of 10°, friction angle of 36°, and shear stress ratio of 0.33.

As shown in Figure 2, the PDC cutting tooth is assumed to be a discrete rigid body. A reference point (RP) is set at the center of the rock, and the PDC cutting tooth is connected to the reference point through rigid body constraints. Surface-to-surface contact is established between the PDC cutting tooth and the rock, with a friction coefficient of 0.3 set in the contact configuration. Meanwhile, through the reference point, a weight-on-bit (WOB) of 1000 N is applied in the Z-direction, and a rotational speed of 60 r/min is applied in the X-direction to complete the load setting for the PDC cutting tooth. In the simulation analysis of axial-torsional composite impact rock-breaking, the bottom of the rock is fully fixed to restrict its degrees of freedom in the X, Y, and Z directions. A sinusoidal shock wave, as shown in Figure 3, is applied to the RP using the Amplitudes module in ABAQUS, with a maximum amplitude of 1.2, a minimum amplitude of 1, and an impact frequency of 12 Hz.

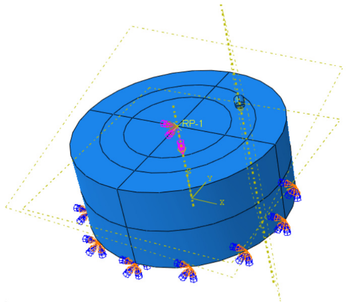


Figure 2. Schematic diagram of boundary conditions

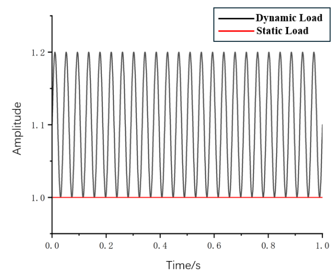
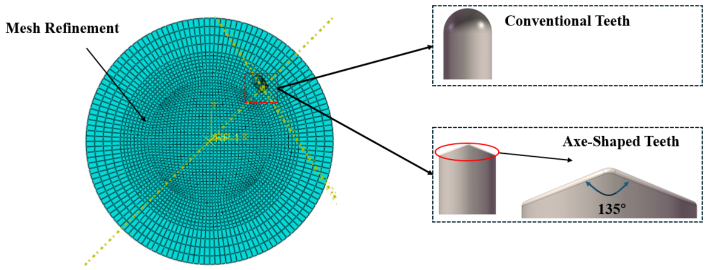


Figure 3. Sin shock wave

3.3. Material Properties and Boundary Conditions

A rock model (with a cylindrical shape, defined by diameter) and PDC cutting tooth models were established. Specifically, the rock model has a height of 150 mm and a diameter of 180 mm. For the PDC cutting teeth: the conventional PDC cutting tooth has a diameter of 8 mm and a height of 13.44 mm; the PDC axe-shaped cutting tooth has a diameter of 8 mm, a length of 13.44 mm, and an axe edge angle of 135°.

To ensure calculation accuracy, the rock model was divided into multiple parts, and local mesh refinement was performed on the region of the rock that would be cut by the PDC cutting teeth. The mesh was assigned the attribute of linear hexahedral elements with reduced integration and hourglass control (element type: C3D8R). The rock model consists of 103,244 meshes, while each PDC cutting tooth model consists of 1,408 meshes. Meanwhile, the element deletion function was enabled.



Figute 4. PDC cutting tooth 3D model

4. Results Analysis

4.1. Analysis of the Axial-Torsional Composite Impact Process

The axial-torsional composite impact load acts on the PDC cutting teeth in the form of shock waves, and its mode of action is shown in Figure 5. In Phase 1, as the amplitude of the shock wave increases, the PDC cutting teeth gradually penetrate into the rock to break it. With the continuous increase of the shock wave amplitude, when reaching Phase 2, the shock wave amplitude reaches its peak, and at this point, the PDC cutting teeth achieve the optimal rock-breaking effect. Subsequently, the amplitude of the impact force begins to decay. In Phase 3, as the amplitude decreases, the weight on bit acting on the PDC cutting teeth also weakens. Coupled with the reaction force of the rock on the PDC cutting teeth, the PDC cutting teeth start to rise slightly and gradually stop breaking the rock. When reaching Phase 4, the shock wave load reaches its valley value, i.e., the minimum value. The PDC cutting teeth are lifted to a certain height and will perform a new round of impact rock-breaking with the fluctuation of the shock wave load. This cycle repeats, and this is the entire rock-breaking process of the PDC cutting teeth under the action of axial-torsional composite impact.

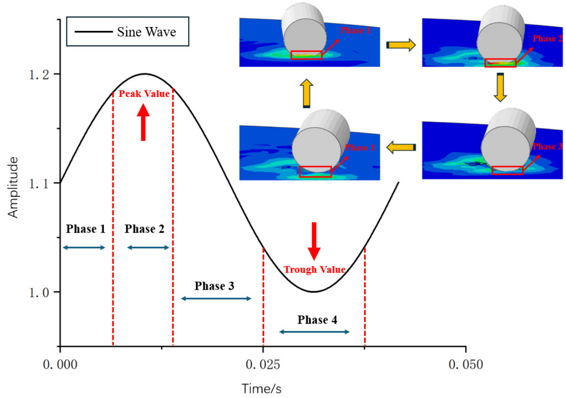


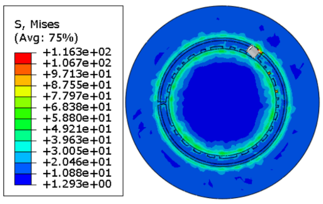
Figure 5. Schematic diagram of compound impact load action

4.2. Comparison of Rock-Breaking Effects

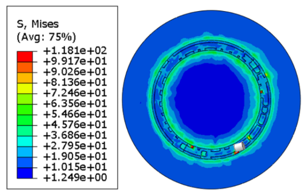
As shown in Figure 6a and Figure 6b, when the conventional PDC tooth breaks rock under normal operating conditions, its stress value is 116.3 MPa; however, when it performs impact rock-breaking under the action of axial-torsional composite impact, the stress value reaches

118.1 MPa. At the same time, as shown in Figure 6c and Figure 6d, when the axe-shaped PDC tooth breaks rock under normal operating conditions, its stress value is 133.8 MPa, while under the action of axial-torsional composite impact, the stress value reaches 175.6 MPa. It can be seen from this that under static loading, stress accumulates slowly, and energy is more concentrated in the contact area. Impact load propagates rapidly inside the rock through dynamic stress waves, resulting in instantaneous stress concentration. Moreover, the dynamic strength of the rock may be lower than its static strength due to the strain rate effect, leading to a higher stress state being more easily achieved.

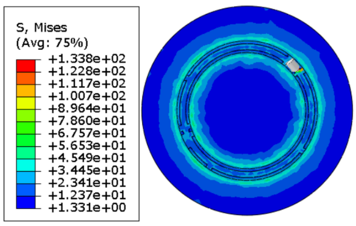
Furthermore, from the rock-breaking process, it can be concluded that the damage caused by the conventional tooth to the rock is mainly concentrated in the area in front of the tooth and around the tooth: the rock in front of the tooth reaches the damage threshold and falls off, while the rock around the tooth is damaged but does not meet the falling-off condition. The damage caused by the axe-shaped tooth to the rock is mainly concentrated in the area in front of the tooth; in addition, due to the special structure of the axe-shaped tooth, it causes deeper damage to the rock in front of the tooth. In general, the axial-torsional composite impact not only increases the rock-breaking depth of the PDC cutting tooth but also accelerates the rock-breaking speed of the PDC cutting tooth, thereby achieving the goal of efficient rock-breaking.



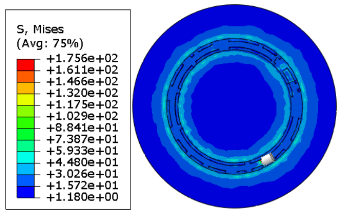
a. Conventional Tooth in Conventional Rock-Breaking



b. Conventional Tooth in Axial-Torsional Composite Impact Rock-Breaking



c Axe-Shaped Tooth in Conventional Rock-Breaking



d Axe-Shaped Tooth in Axial-Torsional Composite Impact Rock-Breaking

Figure 6. Equivalent stress cloud diagram of rock breaking by PDC cutting teeth

4.3. Breaking Depth AND Cutting Force

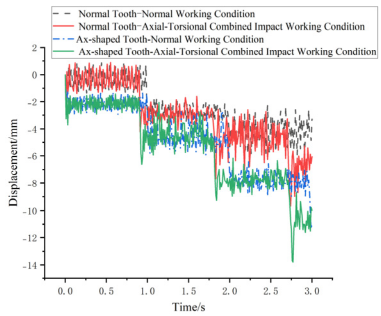
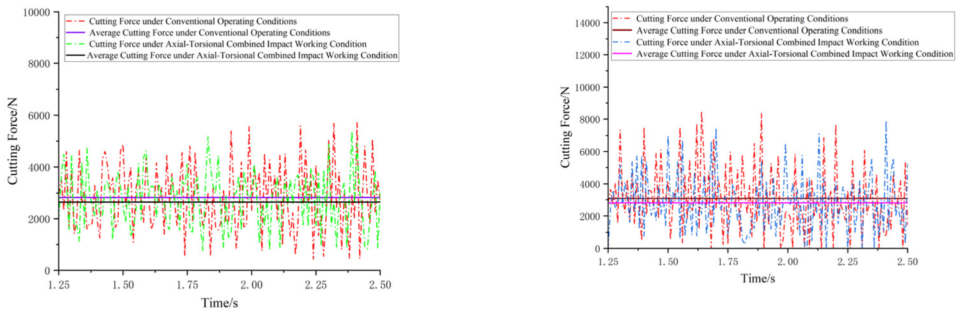


Figure 7. Displacement diagram of rock breaking by PDC cutting teeth

As shown in Figure 7, when breaking rock under conventional operating conditions, the average penetration depth of the conventional tooth is 2.43 mm, and that of the axe-shaped tooth is 4.86 mm—nearly double the difference in their penetration depths. Under the axial-torsional composite impact operating conditions, the average penetration depth of the conventional tooth is 3.05 mm, and that of the axe-shaped tooth is 5.38 mm. It can thus be concluded that, compared with conventional rock-breaking, axial-torsional composite impact rock-breaking can further increase the rock-breaking depth of PDC cutting teeth.

To ensure the accuracy of the results, the initial and final stages of the simulation were excluded. This is because, during the actual drilling process of a PDC bit, both the initial and final stages are unstable, and the results obtained in these stages are inaccurate. Therefore, when simulating the drilling process of the three tooth profiles under the two operating conditions, the simulation results corresponding to the time range of 1.25 s to 2.5 s were selected respectively. This time period represents the stable cutting stage of the PDC cutting teeth, and the results obtained here are more accurate.

As shown in Figure 8a, the average cutting force of the conventional tooth under conventional operating conditions is 2830 N, while under the axial-torsional composite impact operating conditions, it is 2655 N, representing an overall reduction of 6.18% in cutting force. As shown in Figure 8b, the average cutting force of the axe-shaped tooth under conventional operating conditions is 3078 N, and under the axial-torsional composite impact operating conditions, it is 2807 N, with an overall reduction of 8.5% in cutting force. From the above data, it can be concluded that the cutting force under impact load is lower than that during conventional drilling.



a. Cutting Force of Conventional Teeth Under Two Operating Conditions

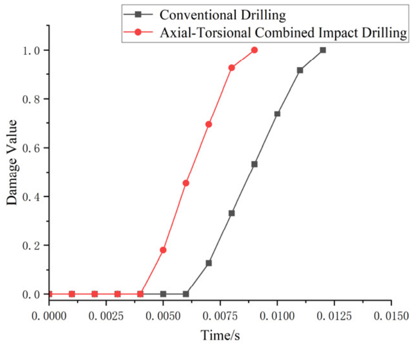
b. Cutting Force of Axe-Shaped Teeth Under Two Operating Conditions

Figure 8. The cutting forces of the three tooth profiles under different conditions

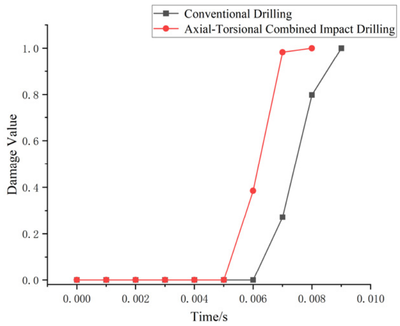
4.4. Damage and Process

To study the damage and failure process, Element a was selected in the rock model, and this element is located directly below the cutting tooth. Here, a damage value of 0 for the element indicates that no plastic failure has occurred in the element, while a damage value of 1 means the element has completely failed.

As shown in Figure 9a, when the conventional tooth breaks rock under conventional operating conditions, the damage value of Element a reaches 1 at 0.0125 s, meaning the element has completely failed. However, when breaking rock under the axial-torsional composite impact operating conditions, the damage value of Element a reaches 1 at approximately 0.0075 s—0.005 s faster overall compared to conventional drilling. At the same time, as shown in Figure 9b, when the axe-shaped tooth breaks rock under conventional operating conditions, Element a meets the failure condition at approximately 0.0095 s; under the axial-torsional composite impact operating conditions, Element a meets the failure condition at approximately 0.008 s. It can thus be concluded that, compared with conventional operating conditions, the axial-torsional composite impact operating conditions, due to their unique operational characteristics, can accelerate the damage of rock by PDC cutting teeth, thereby enabling faster rock detachment.



a. Damage and Failure Process of Element a for Conventional Teeth



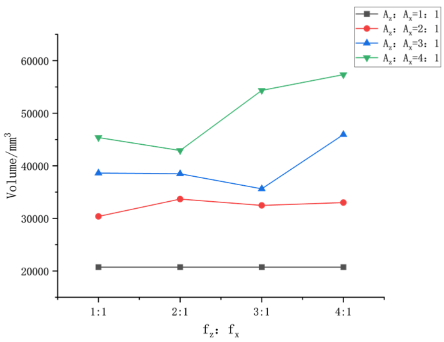
b. Damage and Failure Process of Element a for Axe-Shaped Teeth

Figure 9. The failure history of specific unit damage

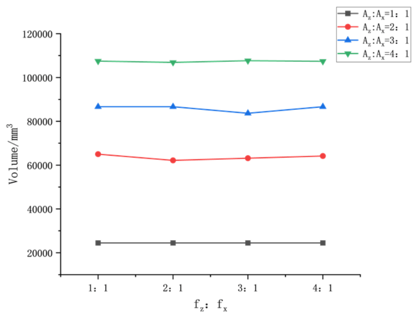
4.5. Analysis of Rock-Breaking Volume and Mechanical Specific Energy Under Different Axial-Torsional Combinations

In the rock-breaking model of this study, the axial impact force adopts a composite action mode of "static load superimposed with dynamic load", and its dynamic variation range is characterized by the fluctuation of weight on bit (N). In contrast, the dynamic characteristics of the torsional impact are reflected by the change in impact velocity (mm/s). To investigate the influence of axial impact parameters on the rock-breaking process, the amplitude (Ax) and frequency (fx) of the torsional impact were kept constant in the simulation analysis, while only the amplitude (Az) and frequency (fz) of the axial impact were adjusted, thereby establishing a variable control system.

As shown in Figure 10a, for the conventional tooth under the impact amplitude ratios of 1:1 and 2:1, if only the impact frequency is increased, the rock-breaking volume of the conventional PDC tooth shows almost no change. When the impact amplitude ratio is 3:1, the rock-breaking volume of the conventional tooth tends to first decrease and then increase as the impact frequency increases. When the impact amplitude ratio is 4:1, the rock-breaking volume decreases slightly as the impact frequency increases from 1:1 to 2:1; however, starting from an impact frequency ratio of 2:1, the rock-breaking volume increases significantly with the increase in impact frequency, and reaches the maximum value when the impact frequency ratio is 4:1. As shown in Figure 10b, when the axe-shaped tooth breaks rock under different axial-torsional combinations, under the impact amplitude ratios of 1:1, 2:1, 3:1, and 4:1 respectively, its rock-breaking volume does not increase with the increase in impact frequency; instead, it tends to stabilize at a constant value.



a. Rock-Breaking Volume of Conventional Teeth Under Different Axial-Torsional Combinations



b. Rock-Breaking Volume of Axe-Shaped Teeth Under Different Axial-Torsional Combinations

Figure 10. Comparison of rock-breaking volume under the torsional fit of different PDC cutting teeth

Mechanical Specific Energy (MSE for short) is the core parameter used to characterize rock-breaking efficiency and is the most widely applied in relevant research fields. Its physical meaning lies in quantifying the mechanical energy consumed to break a unit volume of rock. From the perspective of breaking efficiency, the value of mechanical specific energy is inversely related to rock-breaking efficiency: the smaller the value of mechanical specific energy, the less energy is consumed during the rock-breaking process, and correspondingly, the higher the rock-breaking efficiency. The specific calculation formula for this parameter is as follows:

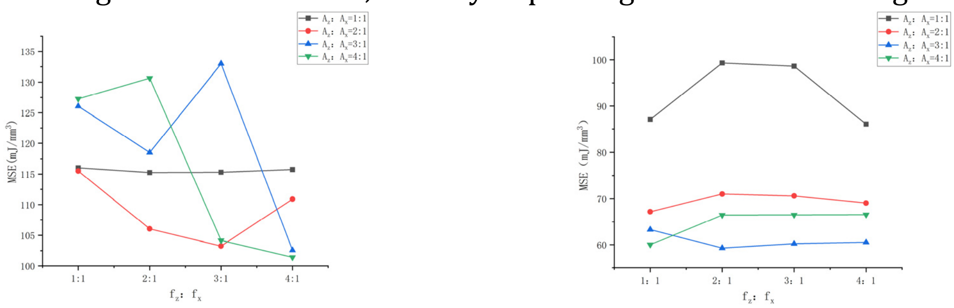
$$MSE = \frac{W}{V} \tag{7}$$

Where: W represents the total energy consumed in breaking rock, with the unit of J; V represents the volume of broken rock, with the unit of mm^3.

As shown in Figure 11a, for the conventional tooth under an impact amplitude ratio of 1:1, its mechanical specific energy (MSE) tends to first decrease and then increase as the impact frequency ratio increases, with a relatively small MSE observed when the impact amplitude ratio is 1:1 and the impact frequency ratio is 3:1. Under an impact amplitude ratio of 2:1, the MSE does not increase with the rise in impact frequency ratio; instead, it relatively stabilizes at a constant value. When the impact amplitude ratio is 3:1, the MSE decreases at impact frequency ratios of 1:1 and 2:1, increases significantly at an impact frequency ratio of 3:1, and then decreases sharply as the impact frequency ratio continues to rise, reaching a low point at an impact frequency ratio of 4:1. Under an impact amplitude ratio of 4:1, the MSE is relatively high at an impact frequency ratio of 2:1 and reaches its minimum at an impact frequency ratio of 4:1.

As shown in Figure 11b, under an impact amplitude ratio of 1:1, the MSE of the axe-shaped tooth exhibits a trend of first increasing, then stabilizing, and finally decreasing as the impact frequency ratio increases, with a smaller MSE observed at an impact frequency ratio of 4:1. When the impact amplitude ratios are 2:1, 3:1, and 4:1 respectively, the MSE does not change significantly with the increase in impact frequency ratio. Notably, the axe-shaped tooth achieves its minimum MSE when the impact amplitude ratio is 3:1 and the impact frequency ratio is 4:1.

In summary, both tooth profiles exhibit relatively small MSE values when the impact frequency ratio is 4:1 and the impact amplitude ratios are 3:1 and 4:1. This indicates that higher impact frequency ratios and higher impact amplitude ratios can reduce the MSE of PDC cutting teeth during rock-breaking to a certain extent, thereby improving their rock-breaking efficiency.



a MSE Values of Conventional Teeth Under Different Axial-Torsional Combinations

b MSE Values of Axe-Shaped Teeth Under Different Axial-Torsional Combinations

Figure 11. Comparison of mechanical specific energy under different coaxial torsional fits of PDC cutting teeth

5. Conclusion

(1) The rock-breaking process of PDC cutting teeth under conventional operating conditions and axial-torsional composite impact operating conditions was simulated and analyzed.

Compared with conventional rock-breaking, axial-torsional composite impact rock-breaking further increases the cutting depth of PDC cutting teeth, accelerates the rock-breaking speed of PDC cutting teeth, and further reduces their cutting force.

(2) Due to its unique operational structure, the axial impact of axial-torsional composite impact rock-breaking is characterized by weight on bit, and its torsional impact is characterized by rotational speed. With the dynamic change of impact amplitude, axial-torsional composite impact rock-breaking accelerates the damage of rock by PDC cutting teeth, thereby improving the rock-breaking efficiency of PDC cutting teeth.

(3) The conventional tooth has the minimum mechanical specific energy (MSE) when the impact amplitude ratio is 4:1 and the impact frequency ratio is 4:1, while the axe-shaped tooth has the minimum MSE when the impact amplitude ratio is 4:1 and the impact frequency ratio is 3:1.

(4) Compared with conventional teeth, axe-shaped teeth are more aggressive in rock-breaking, and their rock-breaking efficiency is higher than that of conventional teeth.

References

[1] Y. Xi, H.Y. Wang, Y. Qi, et al.: Numerical Simulation Study on the Influence of Composite Impact Phase Difference on Rock Breaking Efficiency,*Journal of Petroleum Machinery*, Vol.51 (2023), No.3, p.40-48.

[2] S.B. Liu, H.J. Ni, Y. Wang, et al.: Mechanism of Improving Rock Breaking Efficiency of PDC Bit by Multi-Dimensional Impact,*Journal of Vibration and Shock*, Vol.40 (2021), No.2, p.258-264+278.

[3] S.B. Liu, H.J. Ni, H. Zhang: Development and Application of an Axial-Torsional Composite Impact Tool,*Petroleum Drilling Techniques*, Vol.48 (2020), No.5, p.69-76.

[4] Y. Qi, G.H. Liu, J. Li, et al.: Simulation Study on Multi-Dimensional Impact Rock Breaking Mechanism Based on Single Cutter,*Journal of Petroleum Machinery*, Vol.51 (2023), No.12, p.1-7.

[5] H. Li: Numerical Simulation Study on Rock Breaking by PDC Cutters under Torsional Impact (M.S., Southwest Petroleum University, China 2014).

[6] Y. Yan, Z.C. Guan, L.C. Xuan, et al.: Experimental Study on Rock Breaking Efficiency of PDC Bits under Composite Impact Conditions,*Petroleum Drilling Techniques*, Vol.45 (2017), No.6, p.24-30.

[7] Y.M. Li, T. Zhang, Z. Su, et al.: Simulation Study on the Frequency Matching Characteristics of Composite Impact,*Journal of Petroleum Machinery*, Vol.47 (2019), No.9, p.30-36.

[8] W.J. Liu, Y.J. Zeng, X.H. Zhu, et al.: Rock Breaking Mechanism of Single Cutter under Composite Impact Cutting and Its Comparison with Torsional Impact,*Journal of China University of Petroleum (Edition of Natural Science)*, Vol.44 (2020), No.3, p.74-80.

[9] W. Liu, Y. Xi, C.Q. Zha, et al.: Study on Penetration Depth and Rock Breaking Mechanism of PDC Cutters under Different Impact Drilling Methods,*Xinjiang Petroleum & Natural Gas*, Vol.19 (2023), No.2, p.17-23.

[10] N. V. K, M. A. P.: Determination of Efficient Rotary Percussive Drilling Techniques for Strong Rocks,*Journal of Mining Science*, Vol.57 (2021), No.3, p.447-458.

[11] S.C. Hu, Z.C. Guan, B.P. Lu, et al.: Analysis of Rock Breaking Process and Efficiency of Conical Cutter under Rotary Percussion and Torsional Impact,*Petroleum Drilling Techniques*, Vol.49 (2021), No.3, p.87-93.

[12] K. H, K. F.: Review of Theoretical, Experimental, and Numerical Studies on Rotary Percussive Rock Drilling,*International Journal of Mining, Reclamation and Environment*, Vol.38 (2024), No.2, p.167-191.

[13] Y. Yan, L.H. Han, Y.H. Liu, et al.: Numerical Simulation of Rotary Percussive Rock Breaking Process with Full-Size PDC Bits,*Journal of Petroleum Machinery*, Vol.51 (2023), No.6, p.36-42.

[14] X.H. Zhu, W.J. Liu: Rock Breaking and Rate of Penetration Enhancement Mechanism of Rotary Percussion Drilling Technology,*Acta Petrolei Sinica*, Vol.39 (2018), No.2, p.216-222.

[15] Z. Z. Zhang, D. J. Zhao, Y. Zhao, et al.: Simulation and Experimental Study on Temperature and Stress Field of Full-Sized PDC Bits in Rock Breaking Process,*Journal of Petroleum Science and Engineering* (2022), p.106679.