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Research Article

Working Load Characteristics of the PDC-Cone Composite Bit under Impact and Scraping

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The PDC-roller hybrid bit combines the cutting structure of a tricone bit with a PDC bit. It can achieve good results, breaking rock in directional drilling, drilling in inhomogeneous formations, and drilling in formations with high levels of hardness, and it can achieve the engineering goals of increasing speed and efficiency. First, we analyzed the rock-breaking mechanism of the composite bit and the principles of cushioning, torsion reduction, and prebreaking of the cone teeth during the breaking of rock. Second, cutting load models of the cone teeth and PDC teeth were established through unit experiments and through the calculation methods of the axial force, lateral force and torque, and lateral bending moment of the composite bit. Third, the digital simulation and analysis system was improved to include the function of calculating the working load of the composite bit. Taking an 8-1/2 inch, 2 + 4 type composite bit as an example, the working load characteristics of three cutting structures (cone, blade, and composite) were analyzed and compared. The analysis shows that the composite bit has high drilling efficiency, obvious deviation advantages, and good working stability under specific formation conditions. This paper provides technical support for the performance analysis, formation adaptability evaluation, and cutting structure design optimization of the PDC-cone bit.

1. Introduction

A PDC-cone composite bit, also known as a "cone-PDC hybrid bit," is a drilling tool used mainly for rock cutting that has PDC (polycrystalline diamond compact) teeth on a cutting structure of three-cone bits. The composite drill bit was first proposed by Scott in 1930 [1]. At that time, the fixed cutting structure was in the form of a scraper blade, which was limited by that era's material technology limitations, and was therefore not popularized and applied. With the emergence of various drilling conditions such as high levels of hardness and highly abrasive and uneven layers, higher requirements have been put forward for drill bit performance. With the improvement of the performance index of superhard materials, the possibility of applying a composite drill bit in complicated and difficult-to-drill formations has been reconsidered by technicians. After 2009, Baker Hughes successfully developed the first and second generation Kymera composite drill bits [2], which increased the drilling speed by three to four times, reduced the torque vibration by 50%, and significantly improved the bit's working life [3, 4]. Around 2013, the trial production and batch production of domestic KPM series mixed drill bits [5] and SH series composite drill bits [6] occurred; these bits achieved good results when used in Sichuan, Xinjiang, and other areas where the rock being drilled has uneven texture, hard and plastic formations, and directional drilling condition requirements.

The bit technology research team of Southwest Petroleum University launched "PDC bit digital drilling simulation analysis technology" and supporting software in 2008 [7–9]. This technology can simulate the relationship between the PDC bit and the rock in the complex motion state, calculate the instantaneous cutting amount parameter and the load parameter of the output, and observe changes in the bottom-hole topography in real time.

The rock-breaking mechanism of the PDC-cone composite bit has particular requirements such as a high level of

formation adaptability. In this paper, the digital drilling simulation technology is used to establish the composite bit cutting mechanics function and the digital simulation model of the PDC-cone composite bit, and a set of software systems that can simulate the interaction between the bit and rock is developed. This paper provides effective technical means for studying the mechanical rules, cutting structure design, analysis, and individual new product development of the PDC-cone composite drill bit.

2. Analysis of Rock-Breaking Mechanism of a PDC-Cone Composite Bit under Impact and Scraping

In a PDC-cone composite bit, two sets of cutting structures—the cone cutting structure and the blade cutting structure—jointly contact the rock at the bottom of the hole being drilled. The cone plays a role in the rock-breaking process. This role comprises three aspects:

(1) Cushioning and damping to prevent the impact failure of the PDC teeth. When the drill encounters a heterogeneous formation, the cutting teeth of a conventional PDC bit are prone to frequent changes in the penetration depth of the rock, which leads to the cutting teeth being subjected to a large axial impact load and torsional vibration caused by stick-slip. The cutting teeth are prone to collapse, delamination, or breaking and other abnormal failures, which seriously reduces the service life of the drill bit. However, with the cone-shaped cutting structure of a composite bit, the cone can absorb the drilling pressure and limit the penetration depth of the PDC teeth, so as to protect the PDC teeth and improve the overall impact resistance of the bit.

(2) Producing a precrushing effect on the rock and improving the bit cutting efficiency. The damaged area formed when the teeth intrude into the rock layer (Figure 1) can be divided into three parts: the crushing zone (L_1), crushing compaction zone (L_2), and crack propagation zone (L_3). Except for the crushing pit area (L_1) formed by direct crushing, the residual strength of the rock in the compaction area is very small, and it is easily peeled off at the bottom of the well after subsequent scraping. However, the residual strength in the crack growth zone also decreases significantly, and it is easy to form bulk fractures. The main area, where the teeth cause the precrushing effect, creates a condition for further improving the rock-cutting effect of PDC teeth.

(3) Reducing the working torque of the drill bit and enhancing its ability to deflect. Under the condition of inclined drilling with a conventional PDC bit, the depth of the inner cutting teeth invading the rock is greater than that on the outside, so a great transverse force and lateral bending moment is produced that causes lateral drift of the PDC bit, worsening the stability of the tool surface. The rolling contact mode between the cone and the rock at the bottom of the hole reduces the overall working torque amplitude of the bit, and simultaneously avoids the excessive invasion depth of the inner side of the drill bit, reducing the lateral drift of the bit under the condition of inclined drilling.

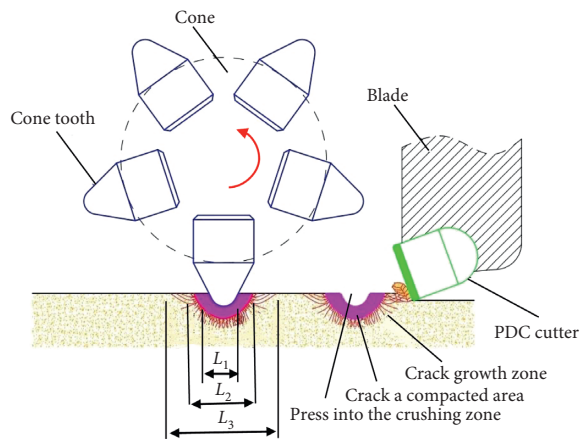


Figure 1: Schematic diagram of the PDC-cone composite bit structure and rock-breaking mechanism.

3. Modeling of the Cutting Mechanics of a PDC-Cone Composite Bit

3.1. Load Modeling of Tooth Cutting. The working load of a PDC-cone composite bit is caused by the interaction of gear teeth and PDC teeth, in which a limited number of teeth on the tooth wheel (i.e., the gear) contact the rock at the bottom of the hole in the form of polygon rolling, forming the interaction relationship of "invasion and slip." A Φ14 mm cuneate gear was used as an example for a unit test, as shown in Figure 2, which shows both the cutter teeth intrusion unit and scraping unit experiments to simulate the processes of "invasion" and "slip," respectively. Three types of rock samples were selected: Nanchong sandstone, Wusheng sandstone, and Beibei limestone.

The influence of different invasion depths and rock strengths on the axial load and tangential load of the cone tooth was studied. Experimental results are shown in Figure 3. The figure shows that the axial and tangential cutting loads of the gear teeth are linearly related to the rock strength and to the modeling functions related to invasion depth index.

Formula (1) gives the axial force of teeth pressing into teeth (F_{Ya}) and the tangential force of teeth pressing into teeth (F_{Yt}):

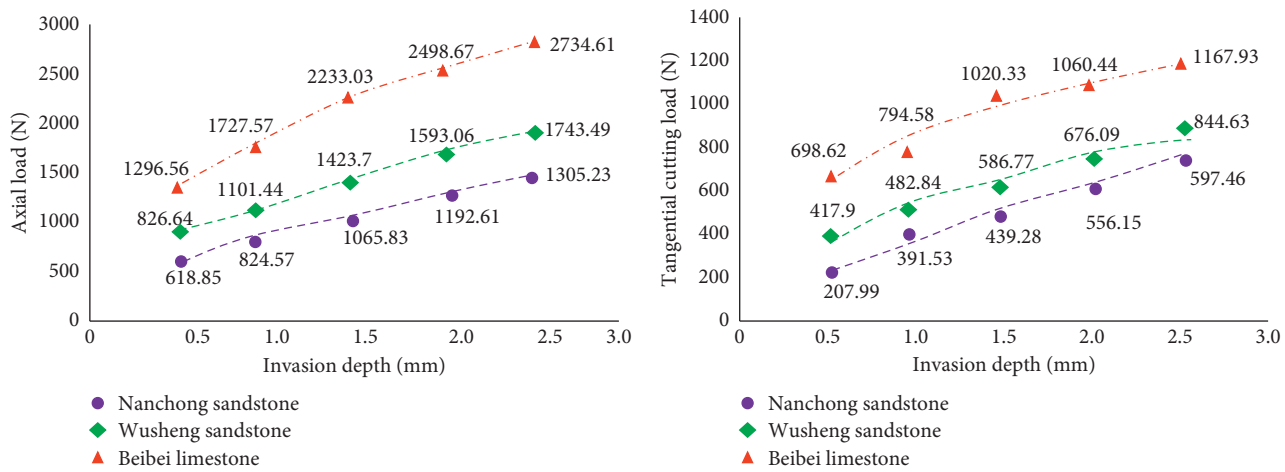
$$\begin{cases} F_{Ya} = 16.86\sigma_c h_0^{0.4758}, \\ F_{Yt} = 6.79\sigma_c h_0^{0.5431}, \end{cases} \quad (1)$$

where σ_c is the rock compressive strength and h_o is the depth of the rock that the teeth penetrate.

3.2. Load Modeling of PDC Tooth Cutting. The rock-breaking process of the PDC tooth and the corresponding load calculation function have been analyzed widely by means of the unit experiment [10–13]. On the basis of the established theoretical formula [14], the influence of brittle fracture on the cutting load of rock by a single tooth cutting test is

(a) (b)

Figure 2: Φ14 mm wedge tooth cutting unit load measurement experiment. (a) Single tooth scraping and cutting experiment. (b) Single tooth invasion experiment.



(a) (b)

Figure 3: Raw data of the tooth cutting load measurement. (a) Trend of axial load change. (b) Trend of tangential load change.

modified. The PDC tooth-cutting load model established based on the unit experiment is as follows:

$$F_{P0} = F_{d0} e^{C_{d1} C_{d2} \alpha}, \tag{2}$$

where F_{P0} is the main cutting force of PDC teeth in conventional cutting state, N; α is the PDC tooth rake angle, °; F_{d0} is the tangential force calculated by theoretical formula when the rake angle is zero, N; C_{d1}, C_{d2} is the correction parameter and correlation coefficient with rock type; and τ_0 is the rock shear strength, MPa.

On the basis of the abovementioned model, considering the predamage effect of gear teeth on rock, the cutting loads of two kinds of cutting structures under different invasion height differences are analyzed [15, 16], as shown in Figure 4(a). The figure shows that the distribution of both tensile stress and compressive stress is common with the predamage of the teeth, which creates favorable conditions for a subsequent PDC tooth to effectively scrape and break the rock.

Figure 4(b) shows the cutting load fluctuation curve of the teeth and the PDC teeth invasion depths of 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm. Statistical analysis shows that when the PDC tooth is 1 mm higher than the tooth of the tooth wheel, the cutting load when scraping to the tooth pit decreases slightly compared with normal scraping, but the range of decrease is not obvious. When the gear teeth are higher than or even with the PDC teeth, the cutting load of the PDC teeth decreases obviously when the teeth are scraped to the tooth pit. Therefore, the intrusion height difference is the main factor that affects the effect of precrushing by the gear teeth. As shown in Figure 5, a linear relationship exists between the cutting load of the PDC teeth in the precrushing area and the conventional cutting load on a flat rock surface.

Therefore, combined with the calculation function of formula (2), the function to calculate the cutting load of PDC teeth in the prebroken area of rock at the bottom of the well can be obtained:

$$F_P = F_{d0} e^{C_{d1} C_{d2} \alpha} (0.634 - 0.332\Delta h), \qquad -1.0 \le \Delta h \le 1.0, \tag{3}$$

where F_P is the main cutting force of PDC teeth under the precrushing cutting condition, N, and Δh is the exposed height of the teeth relative to the PDC teeth, mm.

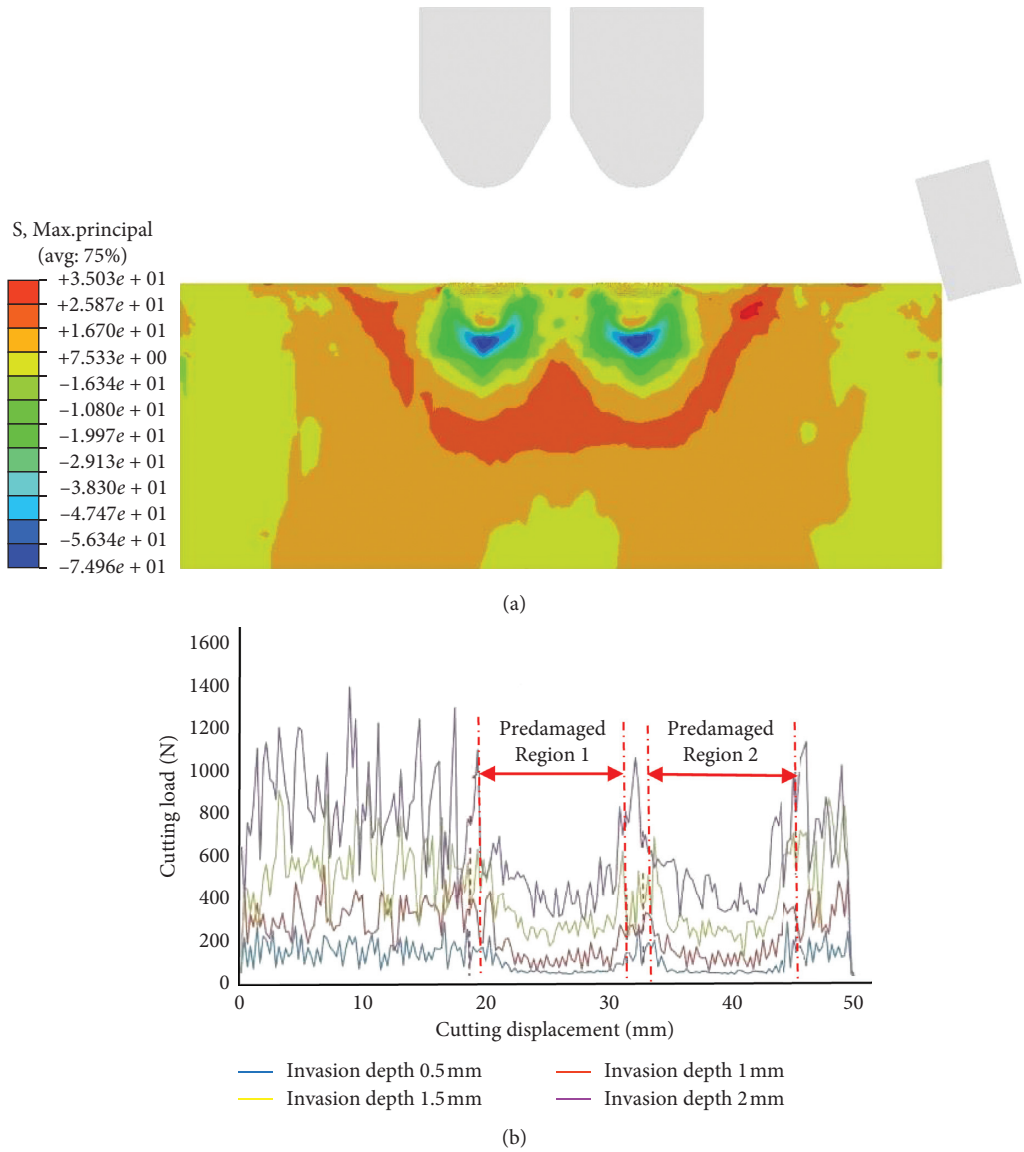


Figure 4: Comparison of cutting load and PDC gear cut rock diagram under predamage action. (a) Distribution of rock stress field during predamage. (b) PDC tooth cutting load curve at different relative heights.

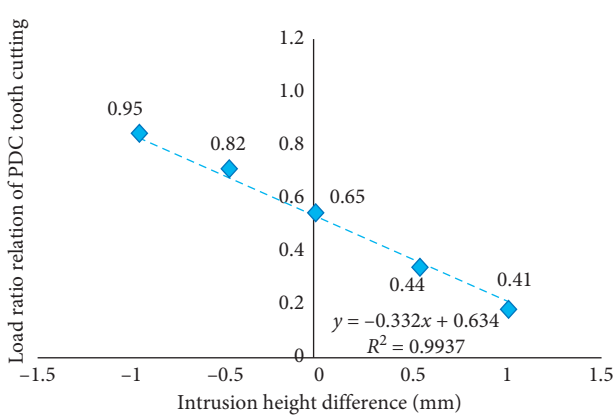


Figure 5: Load ratio relation of PDC tooth cutting with intrusion height difference under two cutting conditions.

4. Establishment of Model of Composite Bit Working Mechanics under Impact and Scraping

The position parameters of the composite bit teeth include the following: radius, C_Y; height H_Y; axial inclination, β_Y; phase angle, φ_Y; radius of teeth, r_y; and height of teeth, h_y. The location parameters of the PDC teeth include the following: positioning radius, r_g; positioning height, h_g; circumferential angle, θ_g; gamma normal angle, γ; rake angle, α; and side angle, β. The PDC tooth coordinate system $O_1X_1Y_1Z_1$, tooth coordinate system $O_2X_2Y_2Z_2$, and composite bit coordinate system $O_0X_0Y_0Z_0$ are used to express and calculate the working load calculation method of the composite bit [17], as shown in Figure 6.

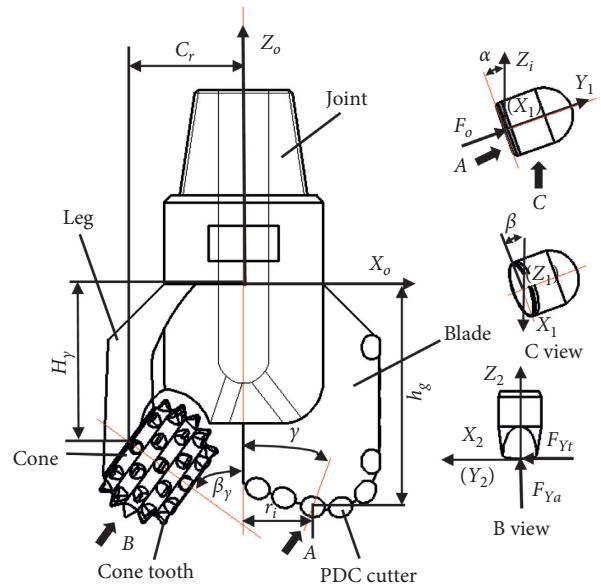


Figure 6: PDC-cone composite bit working load analysis diagram.

4.1. Calculation Model of Axial Force and Lateral Bending Moment of Composite Bit. The axial force load F_z of the composite drill bit can be obtained directly by the set of two cutting loads: that of the lower tooth of the composite drill bit coordinate system and that of the PDC tooth in the axial direction of the drill bit. The calculation model is as follows:

$$F_Z = \sum_{n=1}^{N_Y} F_{Ya}^n \sin\left(\beta_Y^n\right) + \sum_{k=1}^{C_k} F_P^k \sin\left(\alpha^k\right)\cos\left(\gamma^k\right), \tag{4}$$

where N_Y is the total number of bottom contact teeth on the composite bit; F_{Ya}^n is the axial force of the number N contact bottom tooth; β_Y^n is the direction angle of the number N contact bottom tooth, °; C_k is the total number of PDC teeth on the composite bit; F_P^k is the main cutting force of tooth number k of the PDC tooth; α^k is the rake angle of the number k tooth of the PDC tooth; and γ^k is the normal angle of the number k tooth of the PDC tooth.

The compound bit's side-bending moment M_Z is composed of components M_{Zx} and M_{Zy} on the X-axis and Y-axis, respectively, in the bit coordinate system, combined with the side-bending moment M_Z, the side bending moment radius r_M, and the side-bending moment radius angle Φ_M.

$$\begin{cases} M_{Zx} = \left[\sum_{n=1}^{N_Y} F_{Ya}^n \sin\left(\beta_Y^n\right) C_Y \cos\left(\varphi_Y\right) + \sum_{k=1}^{C_k} F_P^k \sin\left(\alpha^k\right)\cos\left(\gamma^k\right) r_g^k \cos\left(\theta^k\right)\right] \times 10^{-3}, \\ M_{Zy} = \left[\sum_{n=1}^{N_Y} F_{Ya}^n \sin\left(\beta_Y^n\right) C_Y \sin\left(\varphi_Y\right) + \sum_{k=1}^{C_k} F_P^k \sin\left(\alpha^k\right)\cos\left(\gamma^k\right) r_g^k \sin\left(\theta^k\right)\right] \times 10^{-3}, \end{cases}$$

$$M_Z = \sqrt{\left(M_{Zx}\right)^2 + \left(M_{Zy}\right)^2}, \quad \text{N·m}, \tag{5}$$

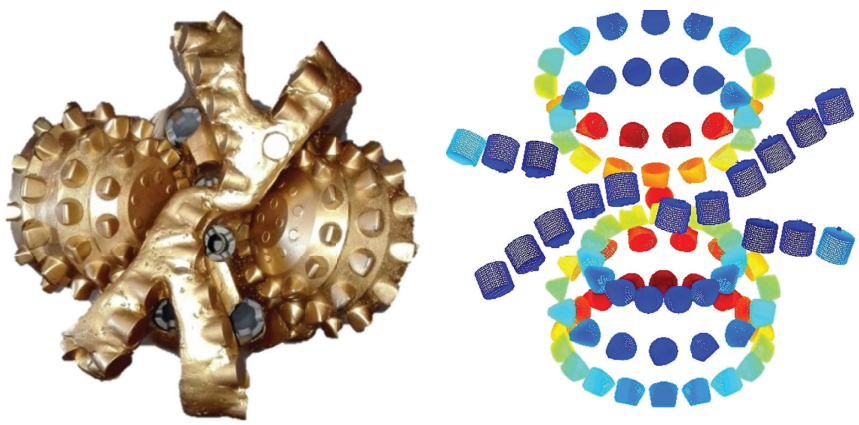
$$\begin{cases} \varnothing_M = a\cos\left(\dfrac{M_{Zy}}{\sqrt{\left(M_{Zx}\right)^2 + \left(M_{Zy}\right)^2}}\right), & M_{Zy} \geq 0, \\ \varnothing_M = 360 - a\cos\left(\dfrac{M_{Zy}}{\sqrt{\left(M_{Zx}\right)^2 + \left(M_{Zy}\right)^2}}\right), & M_{Zy} < 0, \end{cases}$$

where C_Y is the locating radius of roller, mm; φ_Y is the circumferential position angle of tooth wheel, °; r_g^k is the positioning radius of the number k PDC tooth, mm; and θ^k is the circumferential position angle of the number k PDC tooth, °.

4.2. Composite Bit Torque and Transverse Force Calculation Model. The torque of the composite bit T_Z is still composed of the torque load of each cutting unit, which is divided into two parts: cone cutting structure and blade cutting structure.

Table 1: Working load calculation conditions of 8-1/2 inch, 2 + 4 hybrid drill bit.

Rock condition parameter			Drilling condition parameter				
Rock type	Compressive strength	Internal frictional angle	Drill ability	Rate of penetration	Well depth	Rotation speed	Ratio of velocity between cone and bit
Nanchong sandstone	67.55 MPa	38.03°	5.48 (PDC)	6.5 m/h	3500 m	80 r/min	1.3



(a) (b)

Figure 7: Diagrams of the 8-1/2 inch, 2 + 4 type composite bit (a) Composite bit physical model. (b) Composite bit simulation model.

$$T_Z = \left[\sum_{n=1}^{N_Y} F_{Yt}^n C_Y + \sum_{k=1}^{C_k} F_P^k \cos\left(\alpha^k\right)\cos\left(\beta^k\right) r_g^k\right] \times 10^{-3}, \quad \text{N·m}, \tag{6}$$

where β^k is the side angle of the number k tooth of the PDC tooth.

It is necessary to find out the component of each cutting tooth along the coordinate axis on the bit coordinate coefficient first and then to carry out the vector calculation.

$$\begin{cases} F_{Rx} = \sum_{n=1}^{N_Y} F_{Ya}^n \cos\left(\beta_Y^n\right) + \sum_{k=1}^{C_k} F_P^k \cos\left(\alpha^k\right)\sin\left(\beta^k\right)\cos\left(\theta^k\right), \\ F_{Ry} = \sum_{n=1}^{N_Y} F_{Ya}^n \cos\left(\beta_Y^n\right) + \sum_{k=1}^{C_k} F_P^k \cos\left(\alpha^k\right)\sin\left(\beta^k\right)\sin\left(\theta^k\right), \end{cases}$$

$$F_R = \sqrt{\left(F_{Rx}\right)^2 + \left(F_{Ry}\right)^2}, \quad \text{N},$$

$$\begin{cases} \varnothing_R = a\cos\left(\dfrac{F_{Ry}}{\sqrt{\left(F_{Rx}\right)^2 + \left(F_{Ry}\right)^2}}\right), & F_{Ry} \geq 0, \\ \varnothing_R = 360 - a\cos\left(\dfrac{F_{Ry}}{\sqrt{\left(F_{Rx}\right)^2 + \left(F_{Ry}\right)^2}}\right), & F_{Ry} < 0, \end{cases} \tag{7}$$

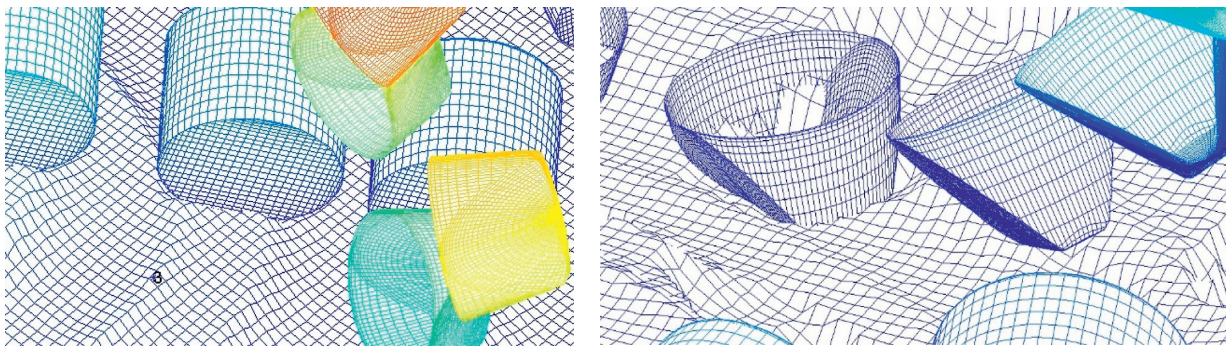
where F_{Rx} and F_{Ry} are the component of the transverse force of the bit in the X and Y coordinate systems; β^k is the PDC side inclination angle of tooth number k of the PDC tooth; and $\varnothing_R$ is the bit transverse force direction angle.

5. Example of Cutting Load Analysis of 8-1/2 Inch, 2 + 4 Type Composite Bit under Impact and Scraping

Using the abovementioned PDC-cone composite bit cutting load calculation model and the composite bit analysis module of the "PDC head digital drilling simulation analysis technology" [7, 18–21], an 8-1/2 inch, 2 + 4 type composite bit was used as an example to carry out a cutting load analysis. Table 1 gives the working load calculation conditions of the drill bit. Figure 7 shows the physical and simulation models of the drill bit, and Figure 8 shows a microcontact relation between the PDC tooth, the tooth gear, and the bottom-hole rock in the simulation analysis.

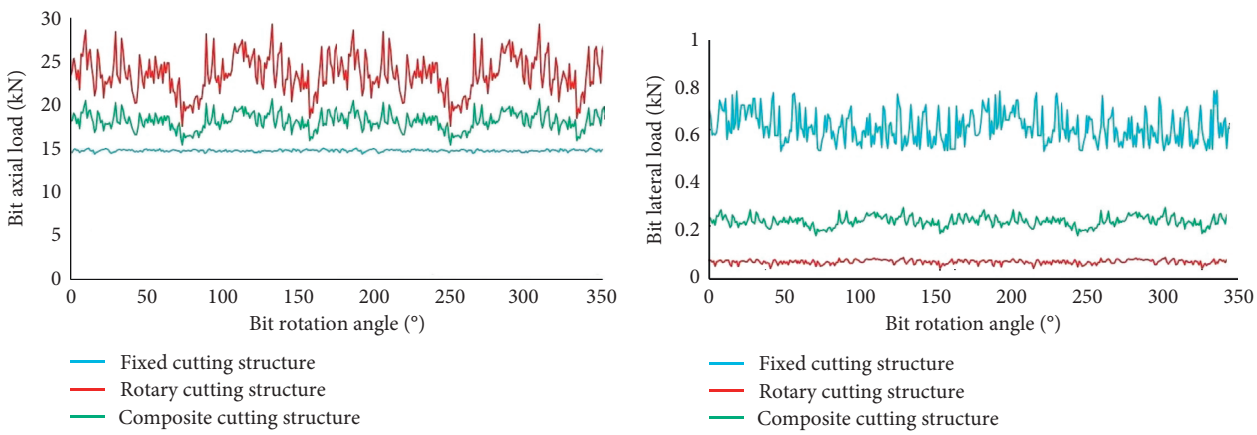
This type of composite bit has a tooth cover tooth envelope 1 mm higher than the PDC tooth cover tooth envelope (i.e., the invasion elevation difference). The main consideration is that the target layer is a medium hard and soft layer with a certain heterogeneity. In the analysis system, the intrusion depth of 2 mm is used for the simulation, and the results of the cone cutting structure, blade cutting structure, and composite cutting structure of the bit are analyzed and compared.

Figure 9 shows that the axial load amplitude of the cone cutting structure in this type of drill bit is the highest; the rolling impact of the cone makes it fluctuate periodically and violently. The transverse load amplitude is the lowest because there is no wheel shift in this structure, and the teeth of the cone press into the rock in the vertical direction. The second highest amplitude is that of the composite cutting structure; the axial load is less than that of the cone cutting structure, and less than the superposition of the other two. The transverse load amplitude is also between that of the blade cutting structure and the cone cutting structure.



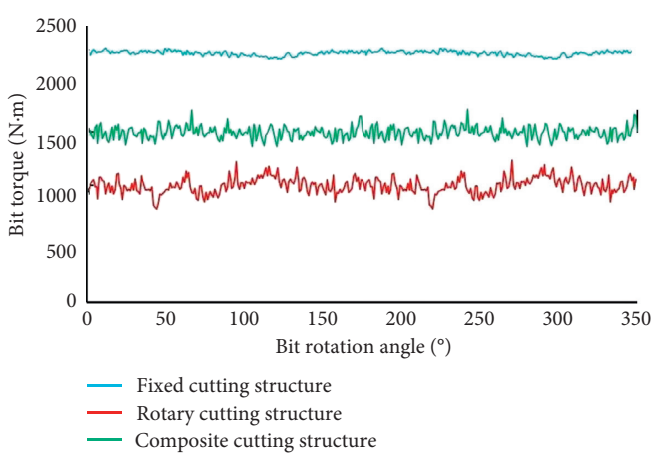
(a) (b)

Figure 8: Digital simulation of combined bit teeth and PDC teeth in contact with the bottom. (a) Bottom contact state of PDC teeth. (b) Bottom contact state of tooth teeth.



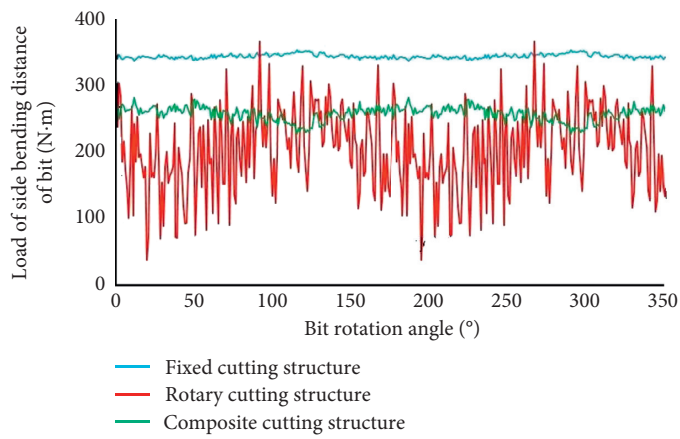
(a) (b)

Figure 9: Comparison of drill bit axial and transverse loads. (a) Bit axial loads. (b) Bit lateral loads.



(a)

Figure 10: Continued.



(b)

Figure 10: Comparison of the torque-side load of the bit torque. (a) The torque of bit. (b) The torque-side load of bit.

Figure 10 shows that both the torque and the lateral bending moment of the blade cutting structure are the largest, and the stability is the best; in second place is the composite cutting structure; and the amplitude of the composite cutting structure is obviously reduced. Although the average load amplitude of the cone cutting structure is the lowest, this amplitude fluctuates sharply, especially the side bending moment load, which shows obvious periodic fluctuation.

6. Conclusions

(1) The PDC-cone composite bit combines the characteristics of the three-cone bit and the PDC bit, and gives full play to the technical advantages of the cone in torsional reduction, vibration reduction, and precrushing through the personalized design of the cutting structure, so as to achieve the engineering goals of significant increases in speed and efficiency when drilling in uneven layers, using directional drilling, and drilling in formations with high levels of hardness.

(2) The difference in exposed height is an important parameter of the composite bit tooth structure and is the key to achieve good vibration reduction and precrushing ability. As a correction factor, it is integrated into the cutting load calculation function of the PDC teeth, and the calculation results can comprehensively reflect the rock-breaking characteristics of the interaction between the two cutting structures of the bit.

(3) By modeling the cutting mechanics and establishing a simulation system, a digital analysis of the rock-breaking process of the composite bit is realized. This analysis can provide an important reference for bit performance analysis, formation adaptability evaluation, and cutting structure design improvement.

(4) In the cutting load of the PDC-cone composite bit, its drilling efficiency is improved compared with that of the cone bit due to the reduction of the axial load. Its incline-building ability is obviously superior to that of the PDC bit due to the reduction of torque. The amplitudes of the transverse force and lateral bending moment are reduced, and the fluctuation is reduced, so that the bit has good working stability.

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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