Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 14, No. 1, 2025

Research and Application of Personalized PDC Bits for Longmaxi Formation in Changning, Sichuan Basin

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Abstract: The Longmaxi Formation in the Changning Block of the Sichuan Basin has a large reservoir thickness and is a high-quality shale for the main shale gas bearing target layer. However, problems such as high rock strength, high drillability level, and large horizontal drilling length in the Longmaxi Formation have led to rapid failure of the drill bit and slow ROP (Rate of Penetration). Research has found that almost all PDC drill bits used in this formation are foreign products, and the drill bits have failure due to core and external cone cutter impact. Therefore, in order to achieve the localization of Longmaxi formation drill bits and the goal of 'one trip drilling', personalized design and application of PDC drill bits are carried out. The rock mechanics property parameters of Changning Longmaxi Shale were obtained by obtaining rock samples on the spot and conducting rock mechanics property experiments. To solve the problem of external cone failure of foreign drill bits, the first generation of axe shaped PDC drill bits targeting the Longmaxi Formation were designed and developed. The average drilling speed of the first generation PDC drill bit is 7.4m/h, which exceeds most PDC drill bits abroad, but is still lower than the highest average drilling speed of foreign drill bits. In order to further improve the bit's invasion ability and directional stability, the profile shape and cutter arrangement of the first generation PDC bit were further optimized, and drilling simulation was conducted. After optimization, the bit's invasion ability and directional stability increased. After optimization, the drill bit footage was 2005m, with an average drilling speed of 10.77 m/h, which was 45% higher than before optimization, far exceeding the highest drilling speed abroad, and achieving the goal of 'ne trip drilling' for long horizontal sections. The successful application of this drill bit provides in-depth understanding and experience for increasing drilling speed in the Longmaxi Formation in Changning.

Keywords: Longmaxi; Shale; PDC bit; Drill optimization; Application.

1. Introduction

With the success of the North American shale gas revolution, shale gas has rapidly become a new hotspot for natural gas exploration and development[1]. The Chuannan shale gas base is currently the largest shale gas production base in China, and the Changning area is one of the most successful areas for shale gas exploration and development in the Sichuan Basin [2,3].

The Longmaxi Formation in Changning area is a high-quality shale with a large and continuous reservoir thickness, which is the main shale gas bearing target layer and has good prospects for large-scale and cost-effective development. However, due to the high mineral content of black shale in Longmaxi Formation (such as silicon and pyrite), the compressive strength and drillability level of the rock are high, and the drilling tools vibrate violently during drilling, resulting in prominent problems such as PDC drill bit tooth breakage and failure of rotating guiding tools and instruments [4-8]. In addition, the length of the horizontal section of Changning shale gas exceeds 1500m, resulting in high wear resistance, severe pressure support, and difficulty in controlling the wellbore trajectory during horizontal drilling [9]. Improving the performance of drill bits is an important means to increase drilling speed and efficiency [10,11]. In order to improve the drilling efficiency of the Longmaxi Formation, this article analyzes the mechanical properties of the Longmaxi Formation rock, and combines the previous research on the use of drill bits in the Longmaxi Formation to carry out drill bit optimization design and application, providing support for low-cost and efficient development of the Longmaxi Formation in Changning.

2. Application Status and Rock Characteristics Analysis of PDC Drill Bits in Longmaxi Formation

2.1. Overall technical status of PDC drill bit drilling in Longmaxi Formation

A survey was conducted on the application of PDC drill bits in the Longmaxi Formation in Yibin, Sichuan. Tab.1 shows the specific application research of PDC drill bits in the Longmaxi Formation. The PDC bits used for drilling in the 2600-5000m section of Longmaxi Formation in Yibin, Sichuan Province, are all in the form of straight five blades and 16mm cutter. The average machine speed of the drill bit varies greatly, ranging from 2.57-8.4m/h. The maximum footage of a single drill bit is 1861.5m, and the drill bit may start drilling due to slower machine speed. As shown in Fig. 1, there is a typical failure situation of the drill bit after it is pulled out. It can be seen that there is a phenomenon of center out at the center of the drill bit, slight wear on the cutter in the inner cone and nose area, and impact failure on the cutter in the outer shoulder area. From this, it can be concluded that the rapid decrease in the invasion ability of the cutter after wear and the insufficient impact resistance of the outer shoulder cutter are the main reasons for the slow speed of the drill bit.

Table 1. Application of PDC bits in Longmaxi Formation

Well No.	Bit No.	Drilling section(m)	Footage(m)	ROP(m/h)
1	PDC bit 1	2733-3520	787	5.72
	PDC bit 2	3520-3559.8	39.8	2.57
	PDC bit 3	3559.8-5060	1500.2	5.68
2	PDC bit 4	2674-4535.5	1861.5	8.4
	PDC bit 5	4535.5-4750.8	215.3	3.14
	PDC bit 6	4750.8-5000	249.2	3.22
3	PDC bit 1	2643-3750	1107	6.34
	PDC bit 7	3750-4711	961	4.05
	PDC bit 7	4711-5320	609	4.46
4	PDC bit 1	2678-3700	1022	7.2
	PDC bit 1	3700-4688	988	6.57
	PDC bit 1	4688-5285	597	7.28



Figure 1. Typical Failure Conditions of PDC bits in Longmaxi Formation

The shape of the profile of the drill bit is an important factor affecting its stability, aggressiveness, rock breaking efficiency, and other working performance. After measuring and analyzing the profile shape of the PDC drill bit in Table 1, it was found that the inner cone range of the profile is between 65~70 °, the nose of profile is about 65mm, and the nose radius is about 36mm.

2.2. Testing of rock mechanical properties in Longmaxi Formation

Based on the investigation of the on-site application of drill bits, in order to gain a deeper and accurate understanding of the mechanical properties of the Longmaxi shale formation and provide data support for the design of drill bits in this formation, on-site outcrop sampling and rock mechanical property parameter testing were conducted for the Longmaxi shale. The sampling site is located in Shuanghe Town, Changning County, Yibin City, Sichuan Province, as shown in Fig. 2 (a). To ensure the accuracy and applicability of rock mechanics parameters, coring was performed on the rock sample, and the core size was obtained with a diameter of 25mm and a height of 50mm, as shown in Fig. 2 (b).



(a) Rock sample collection (b) Rock sample processing (c) Three-axis rock testing machine

Figure 2. Rock sample collection, processing, and experimentation

Three sets of rock cores were selected for uniaxial and triaxial rock mechanics experiments, which were conducted on the triaxial rock testing machine at Southwest Petroleum University, as shown in Fig. 2 (c). The experimental confining pressures are 0MPa, 10MPa, and 20MPa. The stress-strain curve of Longmaxi shale obtained from the experiment is shown in Fig. 3, and the ultimate stress under various confining pressures is obtained. The ultimate stress under 0MPa confining pressure is the unconfined compressive strength of Longmaxi shale. The elastic modulus and Poisson's ratio of Longmaxi shale are calculated using the elastic stage of the stress-strain curve under 0MPa confining pressure. Make stress Mohr circles under various confining pressure conditions and make a common tangent (approximate common tangent due to experimental error), as shown in Fig. 4, to obtain the internal friction angle and cohesion of Longmaxi shale. Therefore, the mechanical parameters of Longmaxi shale obtained are shown in Tab.2.

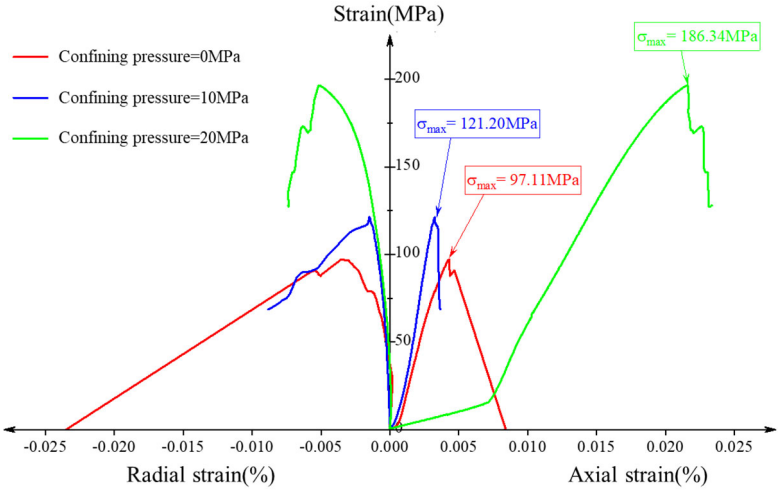


Figure 3. Stress-strain curve of Longmaxi shale

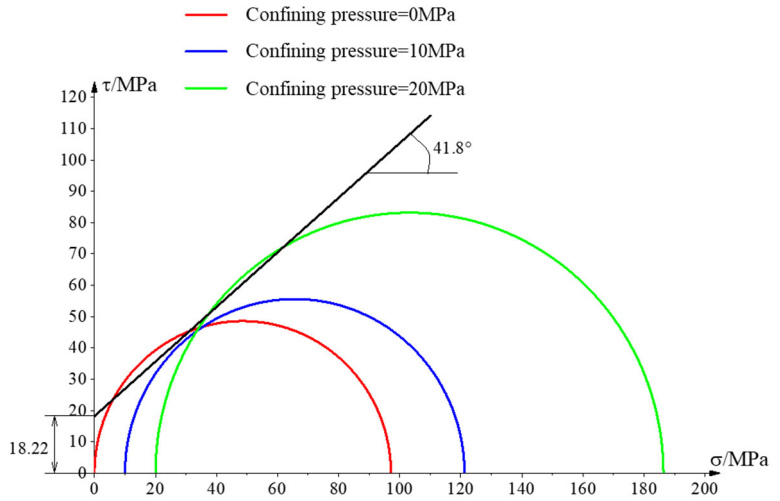


Figure 4. Stress Mohr circles under various confining pressure conditions

Table 2. Rock mechanical parameters of Longmaxi Shale

	Compressive strength (MPa)	Elastic modulus (GPa)	Poisson's ratio	Cohesion (MPa)	Internal friction angle (°)	Density (g/cm3)
Longmaxi Shale	97.11	31.41	0.143	18.22	41.8	2.57

2.3. The first generation self-developed PDC drill bit in Longmaxi Formation

In order to break the foreign monopoly of drilling bits in the Longmaxi Formation, achieve the localization of drilling bits in this formation, and achieve the goal of efficient rock breaking in the horizontal section of shale gas in the Longmaxi Formation with "one trip drilling", based on the analysis of the structural characteristics of foreign drill bits, the summary of the use effect and failure mode of foreign drill bits, and combined with the drilling difficulties in the Longmaxi Formation, the first generation PDC drill bit for the Longmaxi Formation was designed and developed. As shown in Fig. 5, the first generation PDC drill bit's profile curve shape and covering cutter layout diagram are designed. The profile curve shape refers to the drill bit in Table 1. The designed inner cone is 67 °, the nose position is 64.33mm, and the nose radius is 36.18mm. The circumferential tooth arrangement still adopts a straight five blade wing structure. The cutting tooth size is 16mm. Compared to flat teeth, axe shaped teeth have the characteristics of strong invasion ability and high impact resistance, which is conducive to further improving the ROP (Rate of Penetration) of the drill bit [12,13]. Therefore, the arrangement of axe shaped teeth is adopted in the outer cone area of the drill bit. The processed PDC drill bit is shown in Fig. 6.

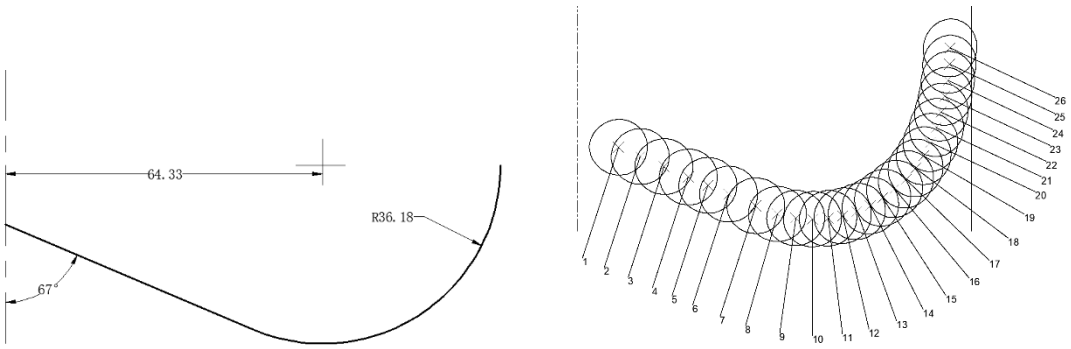


Figure 5. Profile shape and cutter layout diagram of the first generation PDC drill bit



Figure 6. Design and development of PDC drill bits for Longmaxi Formation

The drill bit started drilling in the horizontal section of Ning209H23-1 well at a depth of 3160 meters. When it reached 3505 meters, due to geological stratification advancing by 15 meters and insufficient slope of the rotary guide, it was difficult to enter the target. Therefore, it was necessary to remove the drill and replace the rotary guide instrument. The first drilling depth of this drill bit was 345 meters, with a pure drilling time of 46.5 hours. The average ROP was 7.4 m/h, and the highest ROP was 15 m/h. The average ROP exceeded most PDC drill bits abroad, but was still lower than the highest average ROP of other drill bits (8.4 m/h).

The situation of the drill bit exiting the well is shown in Fig. 7. Analysis of the status of the drill bit exiting the well: The main cutter and retaining teeth of the drill bit are not worn, the body and retaining teeth are intact, and it can continue to be used in the well, achieving the expected effect initially.



Figure 7. Failure of drill bits

3. Optimization Design of PDC Drill Bit Cutter Layout and Simulation Analysis of Bit Drilling

According to the analysis of the failure state of the drill bit after use, it can be concluded that the overall wear of the cutting cutters of the drill bit is relatively small, and the drill bit has a large optimization space. Therefore, in order to achieve the goal of "one trip drilling", the rock breaking efficiency of the drill bit in the Longmaxi formation can be further improved by optimizing the design of the drill bit cutter layout.

3.1. Optimization design of PDC drill bit cutter layout

The most direct way to improve the rock breaking efficiency of the drill bit while ensuring its service life is to enhance its ability to penetrate rocks. This article aims to improve its invasion ability from two aspects: profile shape and cutter structure.

By adjusting the profile shape, the intrusion capability of the drill bit can be improved. 1) The original cone angle of the drill bit was about 67 degrees. Increasing this angle to 78 degrees can also improve the guiding ability of the drill bit. 2) Moving the nose position from the original 64.33mm to 67.33mm and appropriately reducing the profile height by decreasing the nose radius (from 36.18mm to 33.87mm) can shorten the length of the profile curvature segment, enhance the aggressiveness of nose, and optimize the cutting amount distribution. The comparison of profile shape before and after optimization is shown in Fig. 8.

In terms of optimizing the cutter structure, 1) reducing 1 to 2 cutting cutter in the core area can increase the specific pressure of the core cutting cutter, thereby improving the intrusion ability. 2) Reducing the rake angle of the cutter in the central region to 12 ° can also increase the specific pressure of the cutter in the central region and improve the invasion ability. Like the original drill bit, axe shaped cutters are set in the outer cone area of the drill bit, which not only ensures the impact resistance of the external cutter of the drill bit, but also improves the ability of the cutter in this area to invade the rock [14,15]. The optimized cutter-layout is shown in Fig. 9. The structure model of the drill bit before and after optimization is shown in Fig. 10.

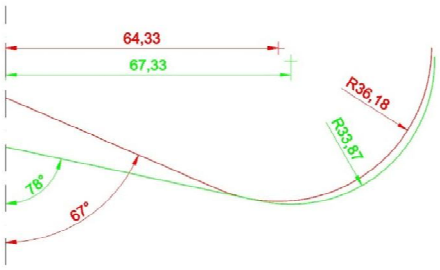


Figure 8. Comparison of profile shape before and after optimization (red represents before optimization, green represents after optimization)

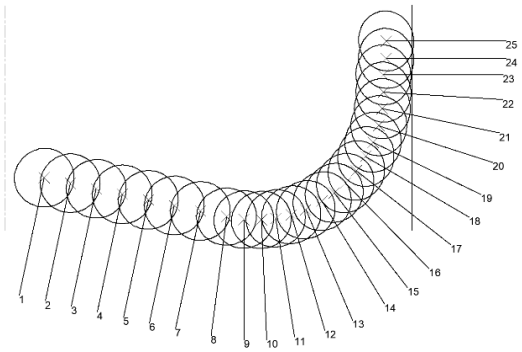


Figure 9. Optimized drill bit cutter layout diagram

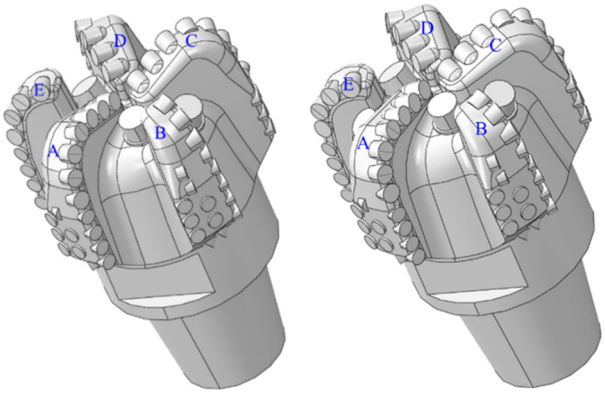


Figure 10. Comparison of drill bit models before and after optimization (left: before optimization, right: after optimization)

3.2. Simulation analysis of interaction between drill bit and formation rock

Fig. 11 shows the simulation model of the interaction between PDC drill bit and rock, as well as the mesh division model of drill bit and rock. The rock model size is 400 × 400 × 200 mm, and the PDC drill bit model is set as a discrete shell rigid body. The grid size of PDC drill bit is 2.5mm, and the grid size of the contact part between the rock center and the drill bit is 2.5mm, gradually increasing outward and downward to 20mm. The mesh type of PDC drill bit is R3D3, and the mesh type of rock is C3D8R. The friction coefficient between PDC drill bit and rock is 0.3. The PDC drill bit applies a velocity of 10.98m/h in the negative z-axis direction and an angular velocity of 60r/min in the negative z-axis

direction through the bound reference point RP-1, while constraining movement in other directions; The rock model completely constrains the motion of the bottom and sides. The rock material adopts the data in Table 1.



Figure 11. Finite element model

The comparison of the average load on each cutter of the drill bit before and after optimization is shown in Fig. 12. Compared to before optimization, the overall optimized cutter load is lower than before optimization, and the stress on the cutter in the nose area of the drill bit is significantly reduced after optimization, which is beneficial for the life of the cutters in the nose area.

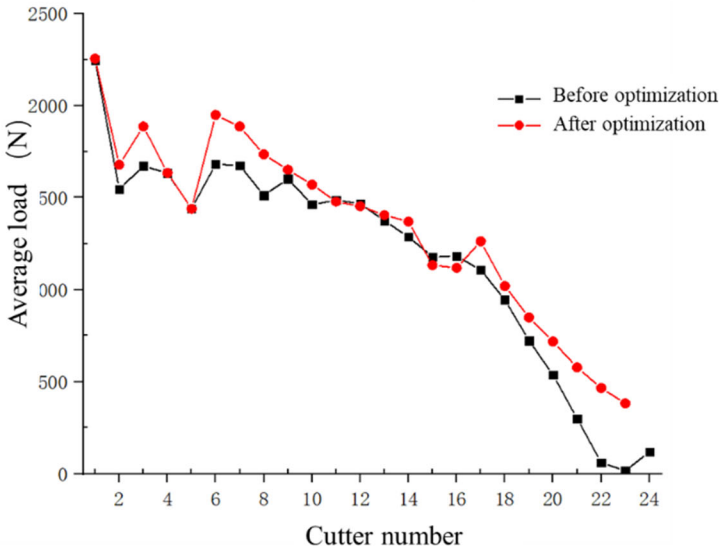


Figure 12. Comparison of average load on each cutter of the drill bit before and after optimization

As shown in Fig.s 13 and 14, the comparison results of drilling pressure and torque before and after optimization for full drill bit simulation drilling are presented. The simulation results of full drill bit drilling show that the average bit pressure before optimization was 18.92kN, and the average torque was 21.79kN · m. During the drilling process, there were severe fluctuations in bit pressure and torque. The simulation results of the optimized full drill bit show that the average bit pressure is 15.95kN, which is 15.7% lower than the pre optimization bit pressure. The average torque is 16.66kN · m, which is 23.5% lower than the pre optimization bit torque. After optimization, the bit pressure and torque are significantly reduced, the bit invasion ability is increased, and the directional stability is enhanced.

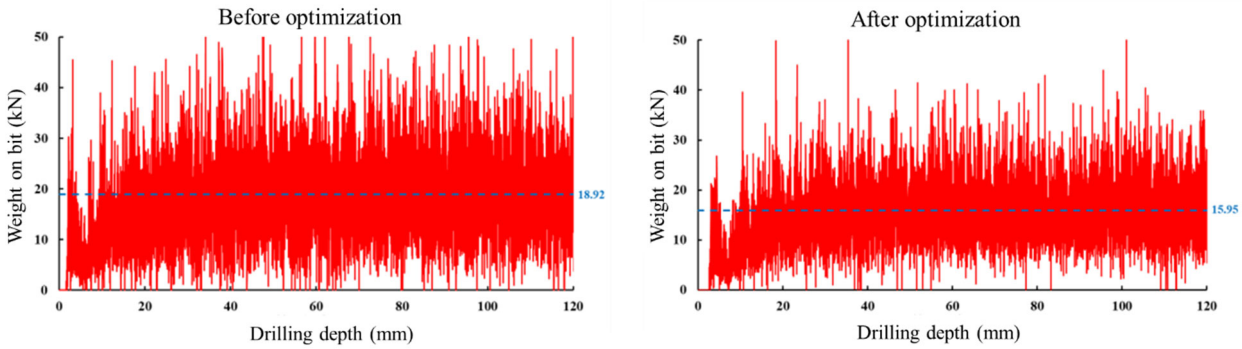


Figure 13. Comparison of Weight on bit before and after optimization

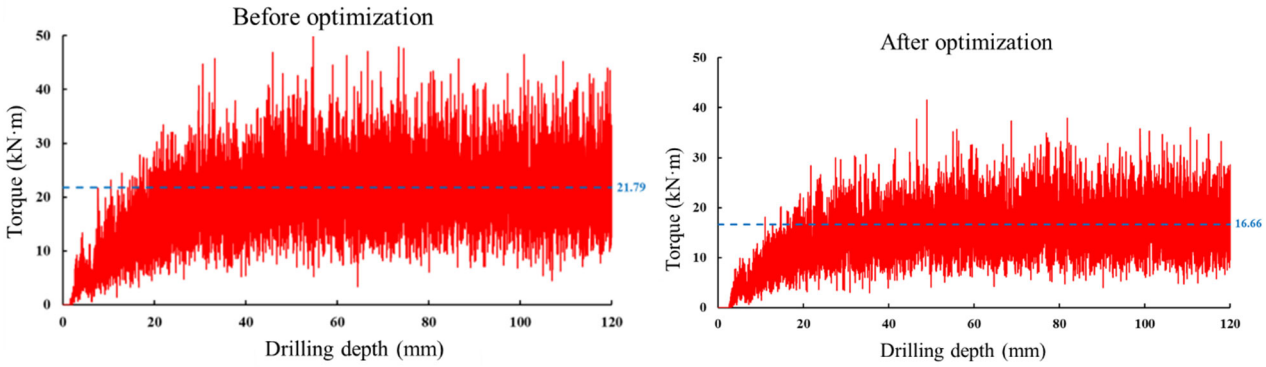


Figure 14. Comparison of drill bit drilling torque before and after optimization

4. Optimized PDC Drill Bit Application

The optimized drill bit was applied in the horizontal section of Longmaxi Formation in Well Ning 209H48-1, with one drill bit entering the well twice in total. The specific situation is as follows.

4.1. First use of drill bit in the well

After optimization and improvement, the drill bit was applied in the Ning 209H48-1 well. Drilling started at a depth of 2545m and when it reached 3907m, the rotary guide instrument had no signal and needed to be replaced. The first drilling depth of the drill bit was 1362m, with a pure drilling time of 87.7h, an average machine speed of 15.53m/h, and a maximum machine speed of 52m/h. The average mechanical speed increased by 84.9% compared to foreign drill bits. The situation of the drill bit exiting the well is shown in Fig. 15. The drill bit has 4 main cutter with a wear of about 2mm, and the 3rd water hole has fallen off. The body and diameter are intact, with a freshness of over 90%, and can continue to be used in the wellbore.



Figure 15. Wear condition of the drill bit after the first drilling operation

4.2. Second use of drill bit in the well

The drill bit started drilling at a depth of 3907m again and completed drilling at a depth of 4550m. The second drilling depth of the drill bit was 643m, with a pure drilling time of 98.5h and an average drilling speed of 6.5m/h. As shown in Fig. 16, the wear condition of the drill bit after the second drilling is examined. The drill bit has 6 main cutters (axe shaped cutter) that are worn out by about 3-4mm, while the remaining cutters are slightly worn, and the body and diameter are intact.



Figure 16. Wear condition of the drill bit after the second drilling operation

The optimized drill bit entered the well from the starting point of the directional section for testing, drilled to the designed depth of the horizontal section, and completed the drilling. The cumulative footage of the two drilling tests was 2005 meters, with a cumulative pure drilling time of 186.2 hours and an average ROP of 10.77 meters per hour. Compared with the drilling performance of the drill bit before optimization, the average ROP increased by 45%, achieving the goal of "one trip drilling" in long horizontal sections.

5. Conclusions

(1) Rock mechanical property experiments were conducted on the Longmaxi shale formation in Changning, and the rock mechanical property parameters of the Longmaxi shale formation were obtained

(2) Based on the on-site investigation of drill bit usage and the shale formation properties of Longmaxi Formation, the first generation five blade axe shaped PDC drill bit was designed and developed for pure drilling for 46.5 hours, with an average ROP of 7.4m/h and a maximum ROP of 15m/h, achieving the drilling purpose preliminarily.

(3) Based on the failure analysis of the first generation axe shaped PDC drill bit, the drill bit was optimized from the profile shape and tooth arrangement structure, and drilling simulation was carried out. The average load of each cutting tooth was reduced before and after optimization, and the drill bit's invasion ability and directional stability were enhanced.

(4) The optimized PDC drill bit was applied on site, and the application showed that the average ROP of the optimized drill bit increased by 45% compared to before optimization, achieving the drilling goal of "one trip" for the drill bit in the long horizontal section of Longmaxi shale formation in Changning.

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