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Development of Specialized PDC Drill Bits for the Interaction of Soft and Hard Strata in Igneous Rocks

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Abstract: ***In response to the technical challenges of low mechanical drilling speed and severe drill bit wear caused by the development of some igneous rocks in the Dongying and Shahejie formations of the Bozhong 34-9 oilfield, it is urgent to develop a specialized PDC drill bit suitable for the soft hard interaction formation of the BZ-34-9 oilfield. The PDC drill bit is required to have strong aggressiveness, as well as good impact resistance and abrasion resistance, in order to meet the drilling requirements of the soft hard interaction formation of the BZ34-9 oilfield. Through on-site use, the mechanical drilling speed has been significantly improved.***

Keywords: Bohai Oilfield, Igneous rock drill bit, On site construction.

1. Introduction

The strata of Bozhong 34-9 oilfield are from top to bottom, including Pingyuan Formation, Minghuazhen Formation, Guantao Formation, Dongying Formation, and Shahejie Formation. The lithology is mainly composed of interbedded sandstone and mudstone with uneven thickness. The Dongying and Shahejie formations have developed some igneous rocks with thicknesses ranging from tens to hundreds of meters. The main rock types of igneous rocks are basalt, andesite, etc. The maximum compressive strength of basalt is as high as 207MPa, belonging to medium to medium hard strata. The rock drillability level is 5-7 levels [1-3], and the drillability is poor; In the early stage, 7 out of 9 exploration wells drilled in the Bozhong 34-9 oilfield encountered igneous rocks [4-5], and the mechanical drilling speed was relatively low, with severe drill bit wear. Among them, BZ34-9-2 well used 4 drill bits to complete the drilling of the 12-1/4 "section (see Figure 1).

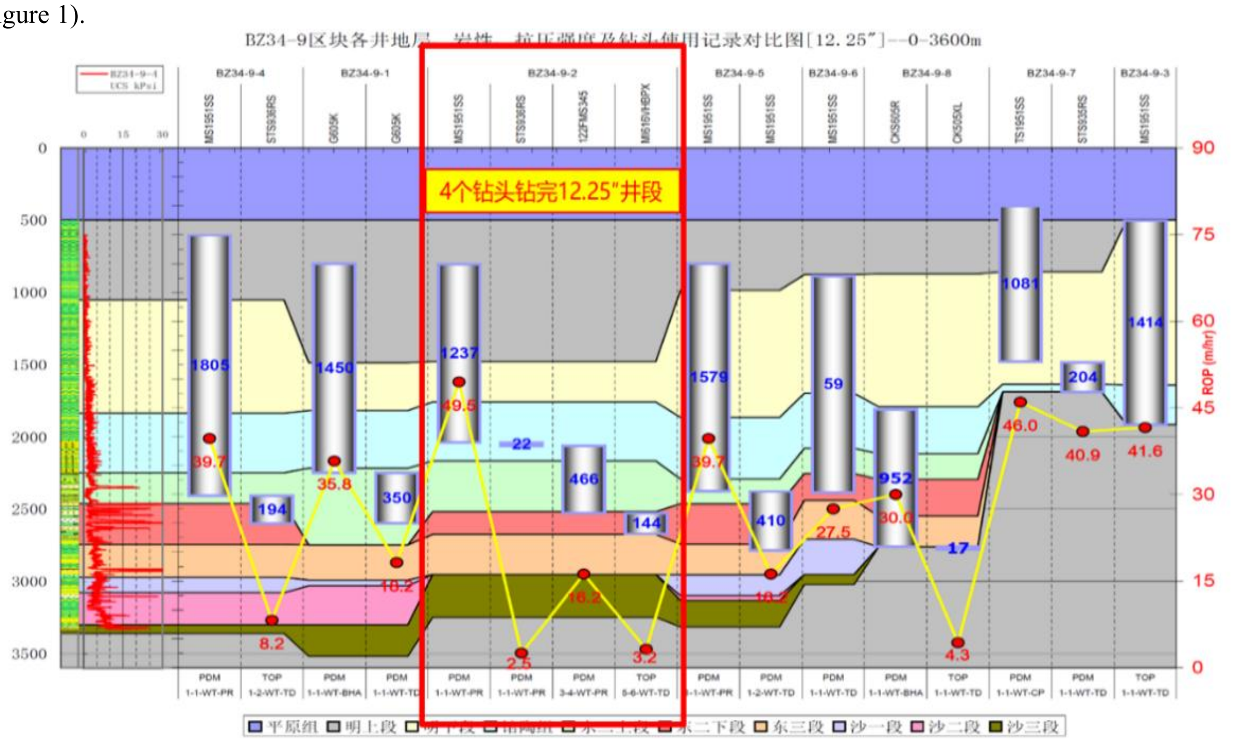

Figure 1: Statistics of Drill Bit Usage in Exploration Wells of Bozhong 34-9 Oilfield

Therefore, it is urgent to develop a specialized PDC drill bit suitable for the soft hard interaction formation in BZ-34-9 oilfield, which requires the PDC drill bit to have strong aggressiveness, as well as good impact resistance and abrasion resistance, in order to meet the drilling requirements of the soft hard interaction formation in BZ34-9 oilfield; To develop the BZ-34-9 oilfield soft hard interaction PDC drill bit, this paper mainly focuses on the following aspects: 1) To reduce the residual stress value of PDC teeth and prevent early failure of PDC teeth, a non planar connected PDC tooth is designed and subjected to anti grinding and impact tests, thus developing a new type of AXE-4 cutting tooth; 2) To ensure that the PDC drill bit has a good stabilizing effect, optimize the diameter retention length of the PDC drill bit and add diameter retention teeth; 3) To ensure the cutting efficiency of PDC drill bits, optimize the design of the camber angle; 4) To improve the chip return ability of PDC drill bits and prevent mud entrapment, numerical simulation of the flow field of PDC drill bits is carried out; 5) To verify the design effect of the PDC drill bit, on-site tests were conducted, and the mechanical drilling speed was significantly improved compared to conventional drill bits.

2. Develop a New Type of AXE-4 Cutting Tooth

Since its introduction in the 1970s, PDC drill bits have been increasingly used in drilling engineering in fields such as oil, gas, and geothermal development worldwide due to their fast drilling speed, long lifespan, high reliability, and significant overall economic benefits in soft to medium hard formations; The actual PDC drill bit is a combination of multiple cutting units, and a single PDC composite piece directly affects the rock breaking efficiency of the PDC drill bit. Its performance directly affects the mechanical drilling speed of the PDC drill bit; PDC composite sheet is a composite superhard material made by sintering polycrystalline diamond (PCD) and hard alloy matrix under high temperature and high pressure (1300-1500° 5-7Gpa) conditions. Although PDC composite is a product composed of diamond with extremely high wear resistance and hard alloy with good impact toughness connected together, due to the significant difference in physical parameters such as thermal expansion coefficient and elastic modulus between the two, there is still a large residual stress at the joint surface during the pressure relief cooling process, which makes the interface of PDC composite the most vulnerable area, causing the diamond (PCD) and hard alloy matrix to easily break or separate, resulting in early failure of PDC drill bits; To effectively reduce the residual stress values at the interface of PDC composite sheets, three non planar connected PDC composite sheets (AXE-1, AXE-3, and AXE-4) were designed and subjected to mechanical analysis using numerical simulation software;

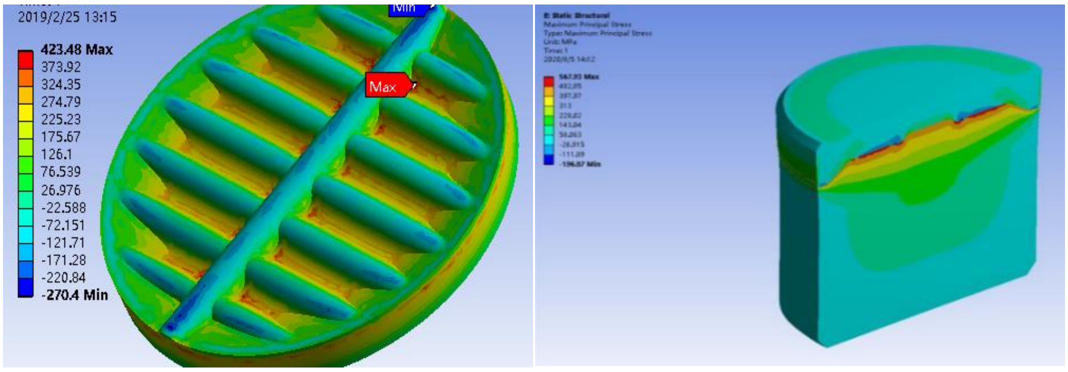

Figure 2: Mechanical numerical simulation of non planar connected PDC composite (AXE-1)

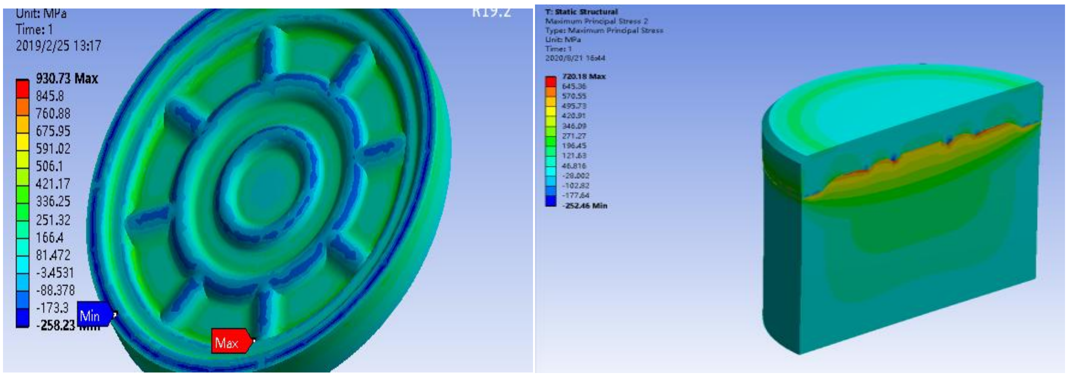

Figure 3: Mechanical numerical simulation of non planar connected PDC composite (AXE-3)

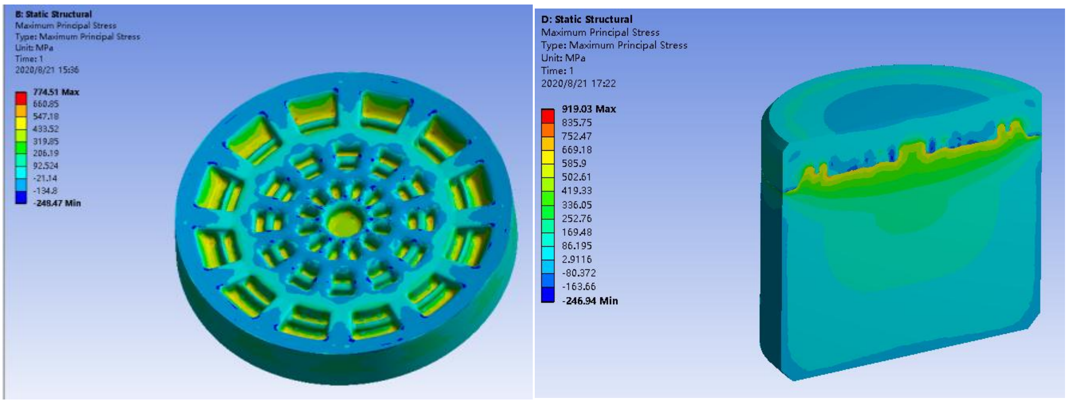

Figure 4: Mechanical numerical simulation of non planar connected PDC composite (AXE-4)

From Figure 2, it can be seen that the maximum residual stress at the PCD (AXE-1) of the "damp insect" non planar connection interface is 421Mpa, and the residual stress is concentrated at the limbs and feet, with relatively concentrated residual stress; According to Figures 3 and 4, it can be seen that the maximum residual stress at the non planar connection interface PCD (AXE-3) of "3D Network Type 1" is 930 Mpa, and the maximum residual stress at the non planar connection interface PCD (AXE-4) of "3D Network Type 2" is 775 Mpa; Compared with AXE-1, the maximum residual stress values inside both are relatively large, but they are more dispersed, and the interface edge is significantly optimized, reducing the risk of PCD layer detachment. AXE-3 and AXE-4 apply a "3D network like" non planar connection interface design to reduce cutting tooth edge stress, and the axially symmetrical joint surface shape allows them to rotate 360° for use. The number of broken teeth is reduced, the degree of broken teeth becomes lighter, and the service life of the drill bit is longer, ensuring that the drill bit can drill efficiently.

In order to verify the impact resistance and abrasion resistance of the three non planar PDC composite pieces (AXE-1, AXE-3, and AXE-4) designed, 15 pieces of each cutting tooth of AXE-1, AXE-3, and AXE-4 were selected, and 5 pieces were tested at 40J, 50J, and 60J for drop hammer impact experiments. The experimental results are shown in Figures 5, 6, and 7.

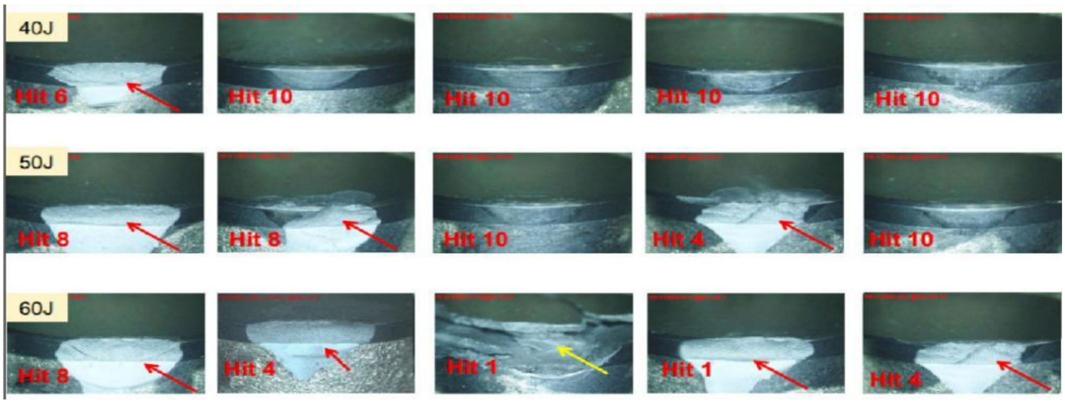

Figure 5: AXE-1's impact resistance performance is tested using a drop hammer impact test

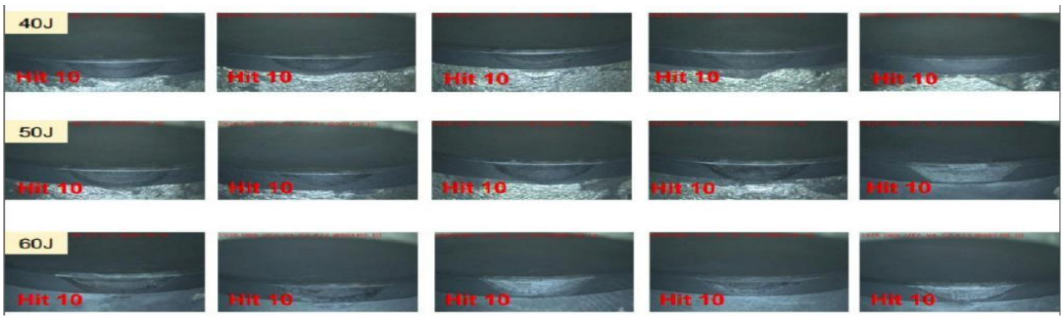

Figure 6: The impact resistance of AXE-3 is tested using a drop hammer impact test

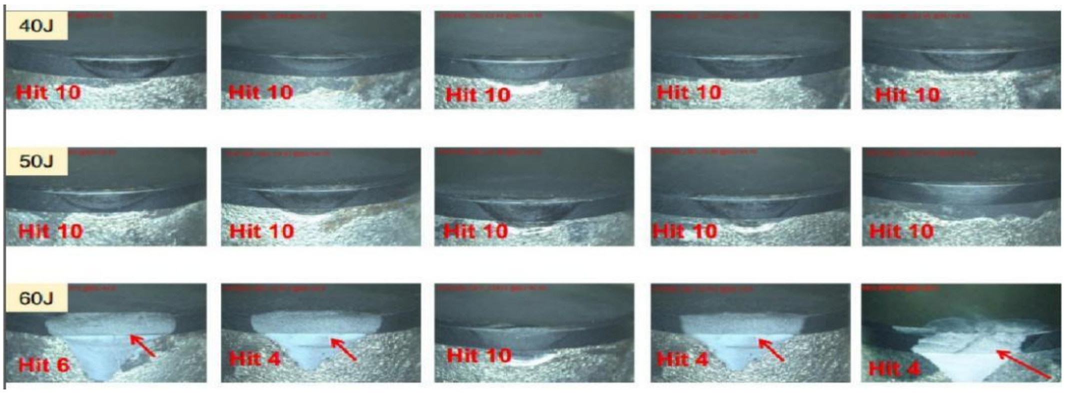

Figure 7: The impact resistance of AXE-4 is tested using a drop hammer impact test

Statistical organization of the experimental results is shown in Figure 8. It can be seen from the figure that when the impact energy is 40J and 50J, the average number of impacts of the three types of cutting teeth is generally similar; When the impact energy is increased to 60J, the number of times AXE-3 can withstand is 52% higher than AXE-1, and the number of times AXE-4 can withstand is 25% higher than AXE-1, indicating that changing the interface shape of PDC composite can effectively improve the service life of PDC composite and reduce the early failure problem of PDC drill bits.

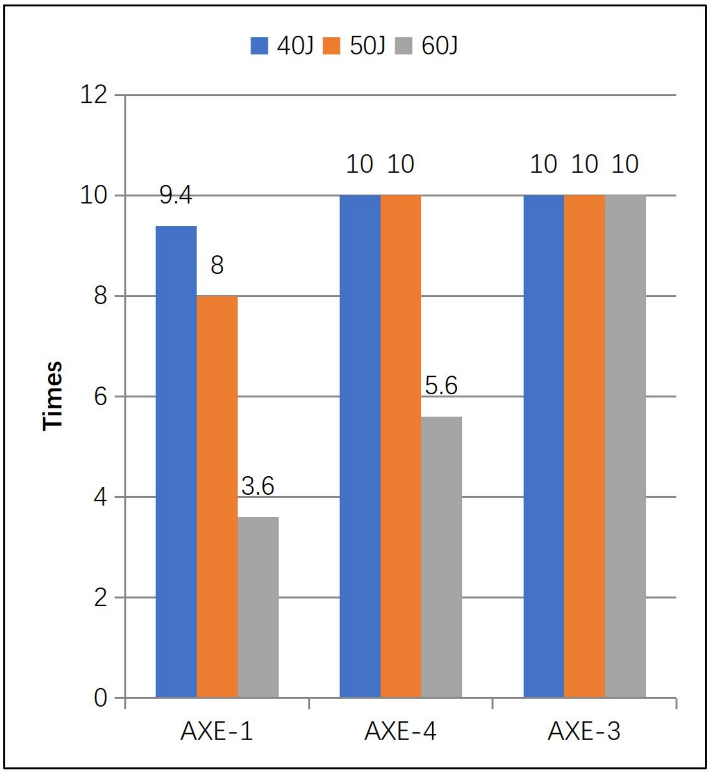

Figure 8: Statistics of Impact Test Data for Each Tooth

The vast majority of PDC drill bits produced during the early stages of well development have varying degrees of tooth breakage and PCD layer detachment. Polycrystalline diamond composite sheets are sintered from diamond micro powders of different particle sizes and hard alloy substrates under the action of cobalt catalyst under high temperature and ultra-high pressure conditions. The Co mass fraction in the diamond layer of conventional PCD layers exceeds 7%, which can promote the conversion of diamond to graphite. When drilling in igneous rock formations, it can cause microcracks in the diamond layer, leading to abnormal damage and detachment of the PCD layer. Under the conditions of ultrasonic environment, temperature of 25℃, and immersion for 40 hours, PDC was subjected to one-step Co removal method, and the Co content was reduced to below 4%. The average volume wear ratio was 6520×10^3, and the anti grinding performance was improved by 10% compared to AXE-1.

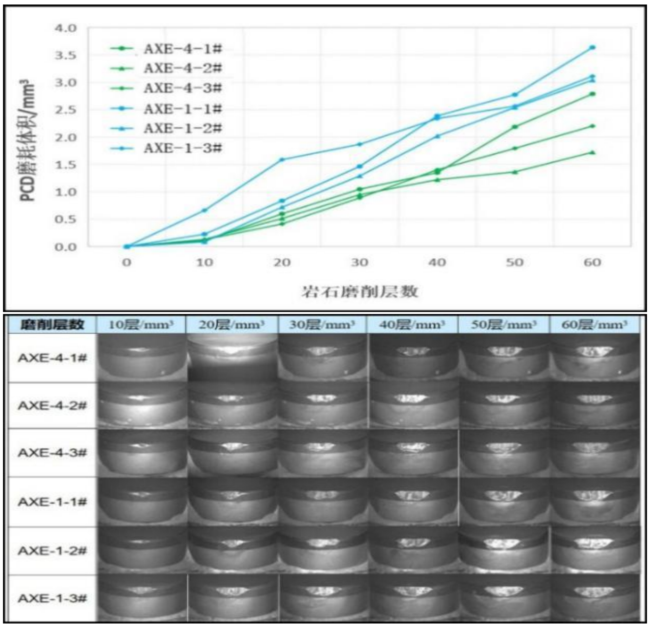

Figure 9: Statistics of Anti Grinding Test Data for AXE Series Cutting Teeth

3. Strengthen and Optimize the Diameter Protection Design

The target layers of the Bohai 34-9 oilfield are the Dongying and Shahejie formations, and most of the wells are conventional directional wells with a depth of 3500-4200m. The stable inclination section exceeds 3000m, and the formation naturally increases by 0.5-0.8°/30m. It is difficult to adjust the wellbore trajectory using a motor drilling tool combination when the well depth exceeds 2500m, so a high requirement for the stable inclination effect of the drilling tool combination is needed. In addition, due to the hardness of igneous rock formations, the wear and tear of the drill bit diameter is severe.

To ensure good stability of the drill bit, the diameter retention length is extended to 3.5 inches, the contact area of the wellbore is increased by 18%, the stability of the drill bit during drilling is improved, the lateral stability of the drill bit is increased, the natural inclination of the formation is reduced to 0.1-0.3°/30m, the frequency of sliding and descending is reduced, and the drilling efficiency is improved; In the case of constant lateral force, increasing the contact area with the wellbore wall reduces the lateral force per unit area, lowers the wear rate of retaining diameter under the same time and lithology conditions, and extends the service life; The extension of the diameter retention life can also reduce the time that cutting teeth are exposed to "harsh" working environments, thereby achieving the effect of extending the life of cutting teeth.

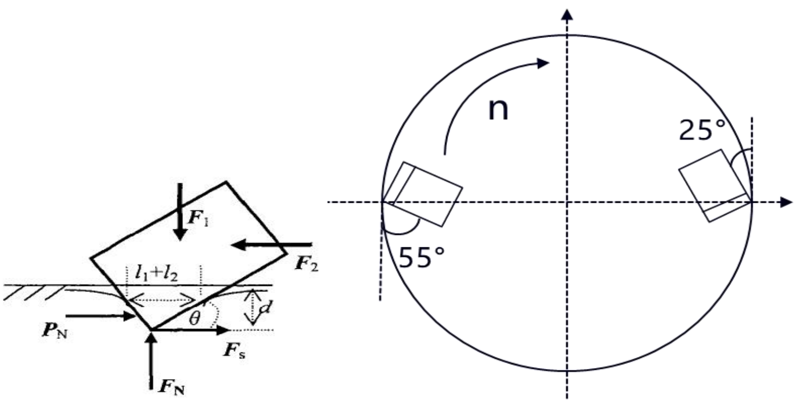

Figure 10: Force analysis of the inclination angle of cutting teeth

To enhance the strength of the diameter retention, an innovative dual row active diameter retention tooth design is adopted. Two active diameter retention teeth are followed by rear row teeth, and the diameter retention block is replaced with a more wear-resistant composite plate. The diameter retention teeth are arranged inside the body for protection. Optimize the back inclination angle of the cutting teeth from 25° to 55°, reduce lateral impact force, weaken cutting effect, enhance centering stability, and extend service life. Arrange reverse serrations on the 45° chamfered surface to prevent blockage during drilling and ensure the safety of the drill bit.

To further improve the wear resistance of PDC drill bits at the retaining point, in addition to brazing composite sheets at the retaining point, a nano-sized WC Co coating is sprayed at the retaining point; Conventional WC Co coatings have been widely used in protective coatings for cutting tools, dielectric barrier layers for large-scale integrated circuits, and gate electrodes in metal/oxide/semiconductor integrated circuits due to their excellent properties such as high hardness, strong corrosion resistance, and high conductivity. They belong to the micrometer scale; Based on the properties of nano coating such as surface effect, small size effect and macro quantum tunnel effect, the WC Co nano film was laser sprayed at the diameter maintaining position of the PDC bit, and the micro hardness test of the WC Co nano coating was carried out by using the HXD-1000TMB digital display micro hardness tester (Shanghai Taiming Optical Instrument Co., Ltd.). The micro hardness reached 2000HV. The MFT-4000 multi-function material surface performance tester (Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences) was used to select the scratch test to determine that the interface bonding force between the WC Co coating and the substrate was 50N. The PDC bit was applied on the site, and its application effect was good, ensuring its downhole safety.

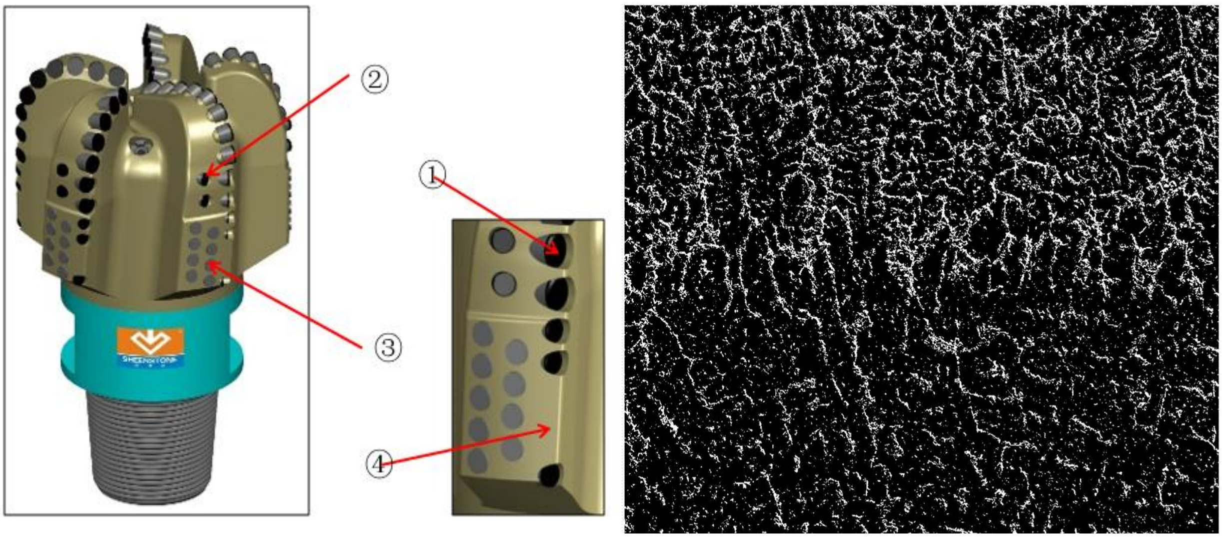

Figure 11: Effect picture after diameter preservation improvement

4. Optimize Crown Shape and Tooth Arrangement

Usually in softer geological formations, the cutting teeth are subjected to less force, resulting in less fragmentation and wear. Using a longer crown profile is beneficial for improving drilling speed and drill bit stability. The outer cone is longer, allowing for more teeth to be arranged, resulting in uniform internal and external wear. In ridge and abrasive formations, a relatively gentle mid short crown section is used to evenly distribute stress and wear the drill bit. Due to the small crown area, drilling pressure and hydraulic action are relatively concentrated, which can be used to improve drilling speed. In response to the characteristics of hard and poor drillability in igneous rock formations, the original 12-1/4 "PDC drill bit was designed with a medium crown profile. In practical applications, the PDC drill bit has ideal machine speed in hard formations, but its aggressiveness is poor in mudstone sections. The subsequently improved PDC drill bit profile was adjusted to a longer crown curve, as shown in Figure 12.

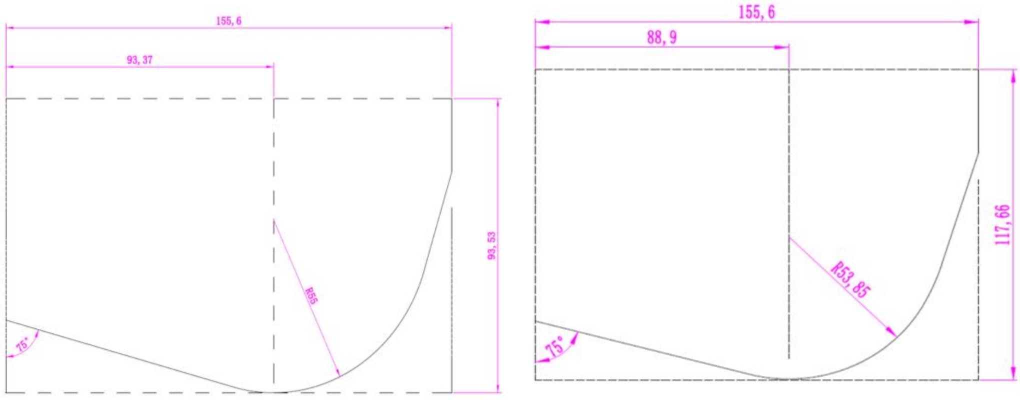

Figure 12: Design diagram of PDC drill bit crown shape

The accelerated wear and impact fracture of cutting teeth are the two main factors affecting the drilling performance of PDC bits in hard and abrasive formations. To improve the wear resistance of PDC drill bits when drilling into igneous rock formations, it is common to choose smaller cutting tooth sizes, increase cutting tooth density, and increase the number of blade blades to enhance the wear resistance of the drill bit. However, high-density tooth arrangement increases the volume of diamond and improves its grinding performance, but the larger contact area usually affects the machine speed; The BZ34-9 oilfield not only contains relatively hard igneous rocks but also large sections of interbedded sandstone and mudstone. After comprehensive consideration, the PDC drill bit adopts a five blade design, with a mixed arrangement of Ø 19mm and Ø 16mm cutting teeth and lower rear teeth arranged behind the main cutting teeth. The five blade design and Ø 19mm cutting teeth design mainly consider the PDC drill bit's strong aggressiveness in soft mudstone formations and its resistance to mud entrapment. The Ø 16mm cutting teeth and rear teeth design mainly consider the drill bit's strong wear resistance and impact resistance in hard formations.

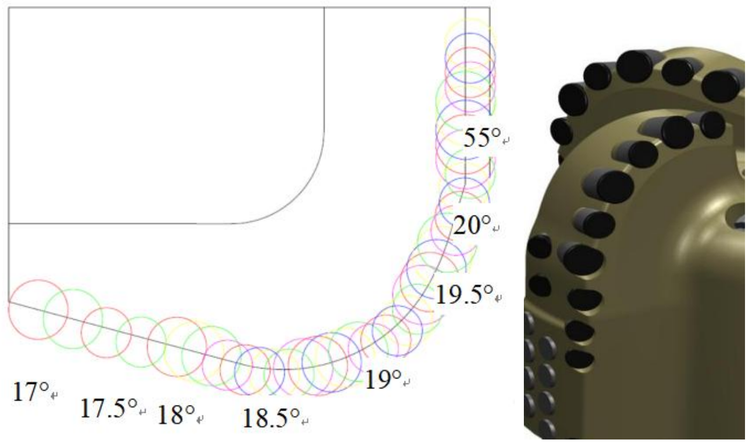

Figure 13: Design diagram of cutting tooth cloth of different sizes

5. Optimizing the Inclination Angle of Cutting Teeth

In response to the poor drillability of igneous rocks, the pre designed igneous rock drill bit used double row teeth, which can cope with the impact resistance of igneous rock formations. However, the drilled formation contains large sections of uneven thickness sandstone mudstone interbedded layers. In soft formations, the attack of the double row teeth design is too weak, resulting in an overall unsatisfactory mechanical drilling speed. In order to fully release the mechanical drilling speed and enhance the aggressiveness of the drill bit, the double row tooth design was changed to a single row tooth design. In order to enhance the impact resistance of the single row tooth, the relationship between the cutting tooth back angle and the rock breaking efficiency was tested. Figure 14 shows the relationship between the cutting tooth back angle and the rock breaking efficiency. According to the experimental chart, the cutting tooth back angle has a significant impact on the rock breaking efficiency of the PDC drill bit. At 15°, the cutting depth per rotation of the cutting tooth is the maximum, and the rock breaking efficiency is the highest. Igneous rock formations can cause certain impact damage to cutting teeth, with a back inclination angle between 15-20°. The cutting ability at the center of the drill bit is minimally affected by the back inclination angle. Therefore, the back inclination angle of the main cutting teeth is designed to be 17-18°, and the back inclination angle of the shoulder teeth with higher linear velocity is designed to be 18-20°. Experiments were conducted on the relationship between the rake angle and impact resistance of cutting teeth, and the relationship between the rake angle and impact resistance was shown in Figure 15. It can be seen from the chart that when the rake angle exceeds 55°, the impact resistance of cutting teeth is minimally affected by the rake angle. The cutting effect of the gauge position is limited, and the wear at the gauge position is particularly severe. In order to better protect the cutting teeth, the inclination angle of the cutting teeth at the gauge position is designed to be 55°.

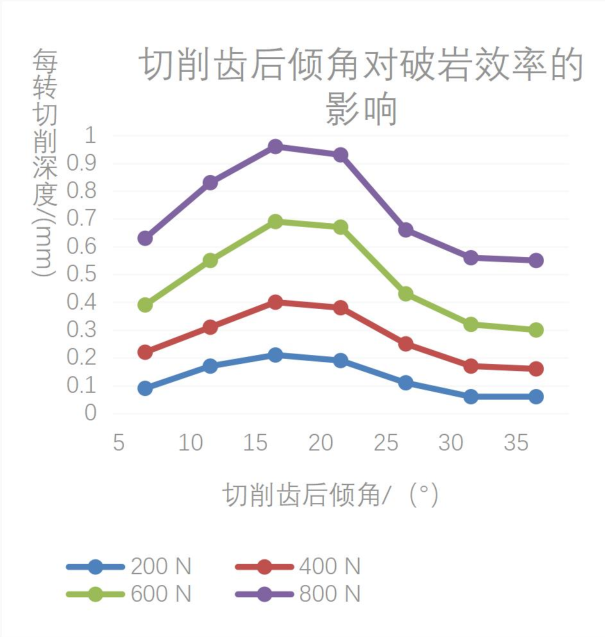

Figure 14: Relationship between the inclination angle of cutting teeth and rock breaking efficiency

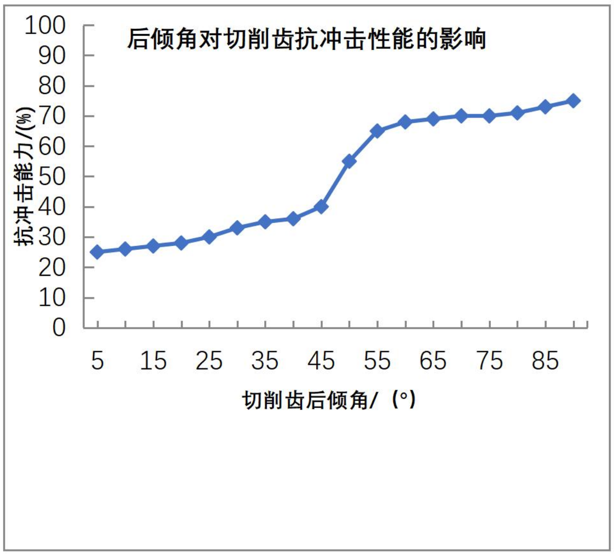

Figure 15: Relationship between the inclination angle and the impact resistance of cutting teeth

Number the cutting teeth in the order of their proximity to the center of the drill bit. The position, size, and angle parameters of each cutting tooth are shown in the table below.

齿号	坐标X	坐标Y	坐标Z	后倾角	侧倾角	刀翼号	齿直径
1	9.59	0.54	2.57	17	0	1	19
2	-16.58	11.1	5.35	17	0	4	19
3	30.28	1.69	8.13	17	0	1	16
4	-37.08	24.82	11.96	17	0	4	16
5	52.41	2.93	14.58	17.5	0	1	19
6	-39.8	-44.47	15.99	17.5	0	3	19
7	-55.24	37.19	17.97	17.5	0	4	19
8	18.69	69.73	19.34	18	0	5	16
9	76.74	3.99	20.55	18	0	1	16
10	38.15	-71.91	21.4	18	0	2	16
11	-57.65	-63.84	21.84	18	0	3	16
12	-75.04	50.87	21.89	18	0	4	16
13	24.98	91.95	21.54	18.5	0	5	19
14	99.93	4.71	20.76	18.5	0	1	19
15	48.39	-92.66	19.6	18.5	0	2	19
16	-73.69	-80.19	18.07	18.5	0	3	19
17	-92.95	64.51	16.16	18.5	0	4	19
18	32.24	112.67	13.89	19	0	5	16
19	121.11	3.8	11.18	19	0	1	16
20	55.78	-111.6	8.24	19	0	2	16
21	-88.48	-92.62	5.01	19	0	3	16
22	-106.16	76.96	1.5	19	0	4	16
23	39.54	127.87	-2.26	19.5	0	5	19
24	136.3	1.39	-6.39	19.5	0	1	19
25	59.31	-125.07	-10.53	19.5	0	2	19
26	-98.89	-99.5	-14.78	19.5	0	3	19
27	-113.33	85.39	-19.13	19.5	0	4	19
28	44.63	136.15	-23.55	20	0	5	16
29	144.65	-0.77	-28.04	20	0	1	16
30	60.64	-132.82	-32.48	20	0	2	16
31	-105.33	-103.07	-36.92	20	0	3	16
32	-117	90.36	-41.53	20	0	4	16
33	47.34	140.04	-46.17	55	0	5	19
34	147.82	-1.75	-51.02	55	0	1	19
35	60.88	-134.71	-55.66	55	0	2	19
36	-105.76	-103.29	-60.3	55	0	3	19
37	-117	90.36	-64.94	55	0	4	19
38	47.34	140.04	-69.58	55	0	5	16
39	147.82	-1.75	-74.22	55	0	1	16
40	60.88	-134.71	-78.86	55	0	2	16
41	-105.76	-103.29	-83.5	55	0	3	16

6. Optimize Lateral Force

The design principle of lateral force balance tooth arrangement requires that the lateral force/drilling pressure of the drill bit be within 5%. Research on the dynamic impact of cutting tooth wear on the lateral force of PDC drill bits shows that during the drilling process, the greater the wear of cutting teeth, the increasing the lateral force, and the lateral force/drilling pressure ratio gradually increases and exceeds 5%, which affects the stable drilling of PDC drill bits, increases the occurrence of harmful movements such as drill bit rotation and vortex at the bottom of the well, and increases the probability of impact vibration of the drill bit.

Therefore, by using a digital drilling simulation system for force balance design, the force analysis and possible wear of PDC drill bits during drilling at the bottom of the well are optimized and adjusted. Considering the lateral force balance tooth structure of dynamic wear of cutting teeth, the drill bit has the minimum lateral unbalanced force and the most balanced load distribution. By using secondary development software to automatically calculate and optimize, the imbalance force of the drill bit was optimized from 4.74% to 3.25%, reducing the occurrence of harmful movements such as drill bit rotation and vortex at the bottom of the well. This is of great significance for the stable rock breaking of PDC drill bits.

Figure 16: Comparison of the Effect of Force Balance Design Optimization Before and After

7. Optimizing the Flow Field at the Bottom of the Well

In recent years, PDC drill bits have been widely used in oil drilling wells. Therefore, studying the flow field of PDC drill bits is of great help for optimizing drill bits and drilling processes. Visualization experiments were conducted on the downhole flow field structure of PDC drill bits using silk thread method and high-speed photography, and it was found that there were strong vortices in the flow channel near the shoulder of the drill bit. The three-dimensional turbulence of PDC drill bit was numerically simulated using computational fluid dynamics technology, and the outlet flow field of PDC drill bit nozzle was tested using particle imaging velocimetry technology. The experimental measured nozzle axial velocity was compared and analyzed with the numerical simulation results, and the two were in good agreement. Numerical simulation was conducted on a rigid PDC drill bit in a rotating flow field, and the streamlines of the drill bit watershed were provided. The drill bit shape was optimized and designed. The improved drill bit was transported to the actual drilling site, which shortened the drilling time and saved drilling costs. There is a backflow phenomenon and vortex generation in the flow channel at the bottom of the well. This is due to the high-speed movement of fluids and the special structure of the wellbore. A nozzle can be placed at the center of the drill bit to alleviate this phenomenon. By optimizing the flow field at the bottom of the well, the hydraulic distribution of the debris removal space can be made more reasonable, which is conducive to better flushing the bottom of the well, carrying rocks, and improving the mechanical drilling speed. After optimization, the W18 * 7 nozzle combination was used, and the maximum flow velocity at the bottom of the well was optimized from 67m/s to 82m/s at a displacement of 3600L/min, an increase of 22%. The hydraulic pressure at the tooth surface position was better, which is conducive to timely cleaning of rock debris, cooling of cutting teeth, reducing the risk of drill bit mud inclusion, and extending the service life of the drill bit.

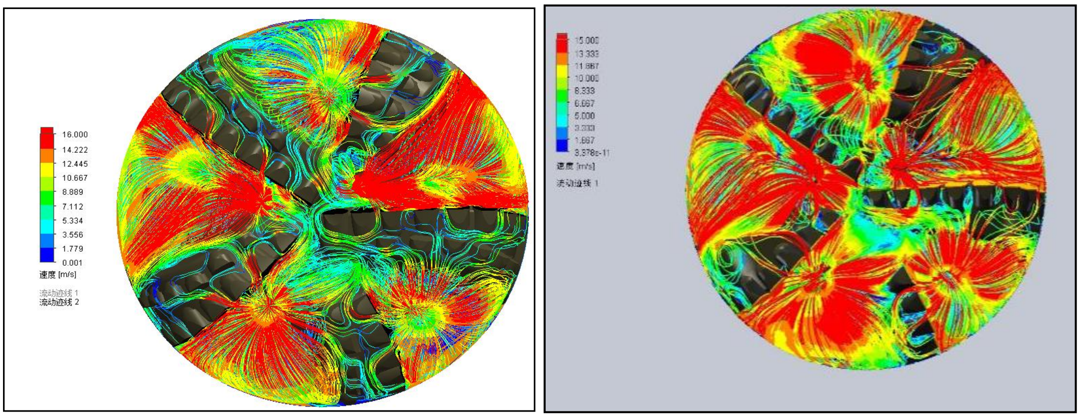

Figure 17: Comparison of Before and After Optimization of Bottom Hole Flow Field

8. On Site Application Effect

Bozhong 34-9 has drilled 9 exploration wells, of which 7 encountered igneous rocks. The PDC drill bit has a mechanical drilling speed of 4.76m/h for igneous rocks, and the Sinopec Xinjiang block has a mechanical drilling speed of 4.59m/h for igneous rocks. We have developed PDC igneous rock specific drill bits with sizes of 8.5 inches and 12.25 inches. During the drilling operation of the Bozhong 34-9 exploration well, multiple PDC drill bits are required for the same section of the igneous rock formation. The wear resistance and impact resistance of the specialized PDC drill bits for igneous rock are greatly improved. With the premise of ensuring the mechanical drilling speed, only one drill bit is needed to complete the same section of the well, and the footage of a single drill bit can reach more than 2800m. 46 wells in the Bozhong 34-9 oilfield were drilled using specialized drill bits for igneous rocks. The mechanical drilling speed for igneous rocks in the 12-1/4 "section was 21.6 m/h, an increase of 188%, while the mechanical drilling speed for igneous rocks in the 8-1/2" section was 17.2 m/h, an increase of 258%. The developed igneous rock drill bit can also be applied to other blocks containing igneous rocks in the Bohai Sea.

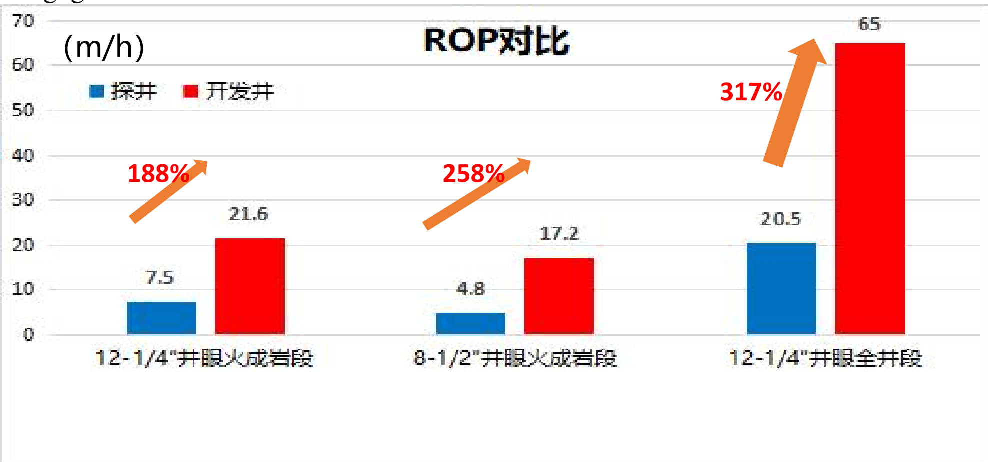

Figure 18: Statistical Chart of Speed up Effect in Bozhong 34-9 Oilfield

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