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A Literature Review on Non-planar PDC Cutter

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ABSTRACT

Since the introduction of PDC bits in 1973, significant advancements have been achieved in drilling efficiency. However, to address the diverse requirements of various formation rocks—such as differences in hardness, strong abrasiveness, and heterogeneity—and to further enhance drilling performance, several companies worldwide have continuously improved upon conventional cylindrical PDC cutters. These efforts have led to the development of a series of innovative geometric designs for novel-shaped PDC cutters. This paper focuses on an investigation of non-planar cutters. It begins by introducing the application background of non-planar cutters and analyzing the current research status and development trends related to non-planar cutters and the rock-breaking mechanisms of PDC, both domestically and internationally. Furthermore, various types of non-planar cutters are enumerated, and their characteristics are described in detail. Regarding the research methodology for non-planar PDC cutters, this paper elaborates on the procedural steps—from the analysis of the rock-breaking mechanism of PDC cutters, to the evaluation of their rock-cutting performance, and finally to experimental analysis. This systematic approach provides valuable guidance for the rational design of non-planar PDC cutters.

KEYWORDS

Non-planar PDC Cutters; PDC Rock Fragmentation Mechanism; Research Methodology; Development Trends.

1. INTRODUCTION

Since its initial introduction by GE in the United States in 1971, the Polycrystalline Diamond Compact (PDC) bit experienced a period of slow development over the following fifteen years. However, subsequent breakthroughs in key technologies spurred a proliferation of research on PDC bits. In parallel, studies on non-planar cutters began to emerge. Early in this research, many investigators observed that once a cutter is fixed onto a PDC bit body, only approximately 30% of its exposed cutting edge directly contacts the rock during the fragmentation process. While increasing the weight on bit can enhance rock-breaking efficiency, it inevitably accelerates the wear of the PDC cutter. Relying solely on improving the interfacial layers or materials of the compact has proven insufficient to address the existing challenges. Consequently, a growing number of researchers have shifted their focus towards modifying the geometric shape of PDC cutters.

Finite element analysis and experimental studies have demonstrated that non-planar PDC cutters engage with rock formations more smoothly. Compared to conventional PDC cutters, they exhibit lower cutting forces and reduced force fluctuations during rock fragmentation. These attributes allow non-planar cutters to penetrate the formation more readily while avoiding the generation of excessive load concentrations.

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Non-planar cutters offer a novel design approach for rapidly drilling through complex formations, shortening the drilling cycle, and reducing operational costs. They have a new path for advancing into deep, ultra-deep, and other challenging hard-to-drill formations. It is anticipated that the ongoing development of non-planar cutter technology will yield significant breakthroughs in mitigating drilling hazards, curtailing non-productive time, lowering overall drilling expenses, accelerating hydrocarbon development, and bolstering the national energy supply.

2. RESEARCH STATUS OF NON PLANAR PDC TEETH AT HOME AND ABROAD

2.1. Current Research Status of Non Planar PDC Teeth Abroad

Since its initial development by the American company GE in 1971, the Polycrystalline Diamond Compact (PDC) cutter has evolved over several decades [1]. Its rock removal mechanism, primarily based on shearing and scraping, has had a profound impact on modern industry. With breakthroughs in key technologies, an increasing number of researchers have engaged in the development of PDC cutters. Currently, PDC bits account for up to 92% of the global oil and gas drilling market [2].

Between 1972 and 1992, a series of advanced PDC cutters were introduced internationally, including the Compax "slug system" PDC cutter [3], the "Syndrill" PDC cutter, and the Layered Diamond Table Cutter—a cutting tool featuring a multilayer polycrystalline diamond structure [4], followed by the Helios cutter. These innovations marked initial progress in addressing the delamination of the diamond layer during drilling operations.

In 1992, Karasawa H and Misawa designed a cutter with a 0.25-mm-thick hard alloy coating and a 0.5-mm-thick diamond cutting edge. This configuration enhanced the cutter's resistance to impact loads [5]. By the mid-1990s, Valdiamant pioneered the claw-shaped cutter based on a non-planar interface, representing the first introduction of the non-planar cutting surface concept in the drilling industry [6].

Subsequent years witnessed extensive international research on non-planar cutters, leading to the development of conical, plow-shaped, and other geometrically complex designs. Major corporations also contributed to this trend: Baker Hughes introduced a shallow-groove non-planar cutter [7], while Schlumberger developed the Stinger center cone cutter [8], ridge-shaped cutters, the ONYX 360° rolling cutter [9], as well as the AXE and Hyperbolic cutters [10].

2.2. Current Research Status of Non Planar PDC Teeth in China

Although domestic research on non-planar cutters commenced relatively late, recent years have witnessed significant advancements in understanding the rock failure mechanisms induced by non-conventional cutters and the cutter-rock interaction, thereby accelerating the development of non-planar cutter technology in China. Chen Lian et al. from Southwest Petroleum University filed a patent for "a polycrystalline diamond compact," proposing several types of non-planar cutters [11].

Wang Xinrui et al. conducted rock fragmentation simulation analyses on multi-ridge PDC cutters, identifying the relationship between ridge angle size and parameters such as tangential force and formation penetration capability [12].

Lin Zhaohu combined finite element simulation with experimental testing to investigate the rock-breaking efficiency of triangular, axe-shaped, and planar PDC cutters, leading to the proposal of a saddle-shaped cutter design [13].

Zou Deyong et al. studied the rock fragmentation mechanism of axe-shaped PDC cutters, finding that this design promotes shear failure in rocks and ensures more stable tangential and axial forces [14].

Liu Hexing et al. examined the rock-breaking mechanisms of ten common non-conventional PDC cutters in challenging formations such as granite, highlighting the superior performance of saddle-shaped and hyperboloid PDC cutters in such environments [15].

Wang Xiyong analyzed the inefficiencies of planar PDC cutters in highly abrasive formations and developed a novel elongated non-conventional PDC cutter to address these limitations [16].

Wei Xiuyan et al. utilized numerical simulations to evaluate the rock-breaking characteristics of triangular cutters under triaxial stress conditions [17].

Zhu Guanghui et al. conducted single-cutter rock cutting experiments to assess the performance of worn cutters under varying wear levels and rake angles, deriving patterns in triaxial forces and temperature during the cutting process [18].

In summary, the design of non-planar cutters represents a theoretical and principled approach to enhancing the overall performance of PDC cutters. The transition from conventional PDC cutters to non-planar and geometrically complex designs is an inevitable trend in the future development of cutting structures.

2.3. Research Status of PDC Cutting Teeth Rock Breaking Mechanism

The PDC cutter serves as the fundamental cutting unit of a PDC bit. Investigating its interaction with rock is essential for understanding the forces acting on the bit during drilling and provides the theoretical foundation for analyzing, researching, and designing novel non-planar cutters. The rock fragmentation mechanism of PDC cutters offers the theoretical basis for the customized design and application of PDC bits. Currently, researchers worldwide have conducted extensive studies on the rock-breaking mechanisms of cutters from three primary perspectives: theoretical investigation, simulation-based design, and experimental analysis.

Simon and Teale analyzed the drilling process from an energy perspective, introducing the concept of specific energy—the mechanical energy required to destroy a unit volume of rock, measured in N/m^2 (Pa). Their experimental study found that the specific energy for rock fragmentation under atmospheric pressure conditions closely approximates the rock's compressive strength [19].

As early as 1947, Hill proposed that failure criteria for ductile materials are not applicable to brittle materials like rock. Goodrich, in 1956, put forward a theory of rock shear failure [20]. B. Paul and D.L. Silkarskie conducted studies on wedge-shaped indenters penetrating into rock and proposed a rock shear failure theory based on the Mohr failure criterion [21]. P.K. Dutta suggested that the wedge action of a compacted core is responsible for inducing shear failure in rock [22]. M.V. Swain and Lawn B.R. proposed a theory of rock tensile failure during indentation [23].

Domestic scholars have also made significant contributions: Yu Jing studied the developmental process of rock fragmentation [24]; Shi Xiangchao et al. summarized research on the rock-breaking mechanisms of bit teeth [25]; Jiang Xin et al. established an impact load prediction model for conventional PDC cutters through impact tests on various rocks [26]; Kuang Yuchun et al. developed a cutting force model for conventional single PDC cutters and verified its feasibility via finite element analysis [27]; Yang Shunhui conducted rock-breaking experiments on five different conical PDC cutters, analyzing fragmentation efficiency under various parameters [28]; Zhao Hang performed experimental and simulation studies on the rock-breaking mechanism of axe-shaped PDC cutters [29]; and Liu Jianhua investigated the rock-breaking mechanism and conducted field tests for non-planar triangular PDC cutters [30].

Substantial progress has been made internationally in both experimental and simulation-based research on single PDC cutter rock fragmentation. However, for the recently developed non-planar cutters, literature on their rock-breaking mechanisms and the factors influencing their fragmentation efficiency remains relatively limited.

2.4. Existing Problems and Current Development Status

China's oil and gas drill bit R&D and manufacturing sector has established a considerable foundation, broadly meeting domestic demands in terms of both quantity and quality. However, despite the large number of domestic drill bit enterprises, most lack scale, with research personnel dispersed and R&D investment insufficient. Consequently, their products still lag significantly behind those of internationally renowned drill bit companies.

Domestic research on non-planar cutters, such as axe-ridge PDC cutters or other 3D geometries, remains in its nascent stages, indicating substantial room for development. There is a notable scarcity of studies focused on the rock-breaking mechanisms of non-planar PDC cutters. Specifically, comparative analyses of the intrinsic performance of different non-planer cutter designs and in-depth investigations into their fragmentation mechanisms are highly limited.

Moving forward, it is imperative to enhance collaboration among academic institutions, strengthen fundamental theoretical research and computational modeling capabilities, and actively track international leading-edge technologies. Continued efforts should be directed toward deepening PDC bit research, improving their performance and quality, and advancing the development of customized bit designs and services. A concentrated focus on analyzing the 3D structures of non-planar cutters and their rock-breaking mechanisms will be crucial for increasing China's market share and competitiveness in the global drill bit industry.

3. OVERVIEW OF VARIOUS NON PLANAR PDC CUTTER

3.1. Foreign Non Planar PDC Cutter

(1) Non-Planar Interface Compacts

The concept of the non-planar interface was initially introduced to address the premature delamination of the diamond layer in compacts during drilling. In the 1990s, the non-planar interface concept was proposed, with the grooved substrate emerging as the most widely adopted technique for compact bonding. This method involves creating intersecting vertical and horizontal grooves on the interface between the diamond layer and the carbide substrate, as illustrated in Figure 2-1 [31]. This design increases the contact area between the diamond layer and the carbide substrate by approximately 22%, resulting in a substantial improvement in bonding strength. Consequently, the implementation of a non-planar interface design for the compact significantly reduces the probability of diamond layer delamination, while also markedly enhancing the wear resistance and impact strength of the bit.

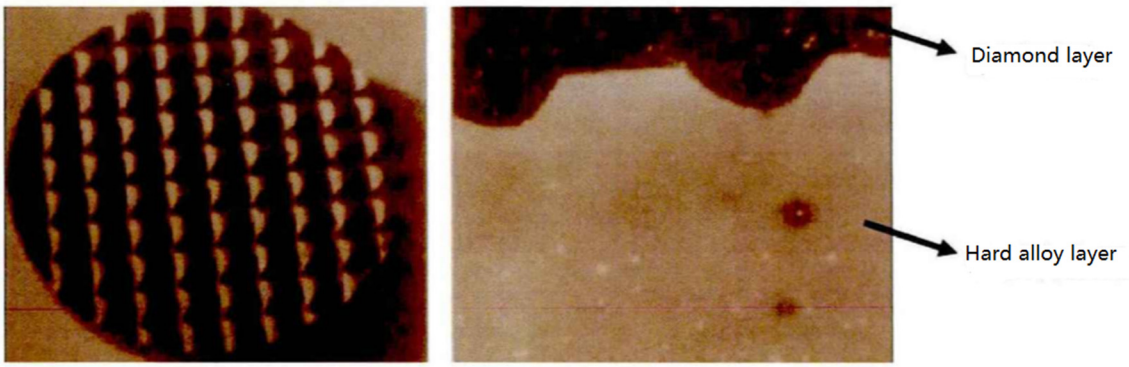

Fig 1. PDC cutting tooth composite sheet with vertical and horizontal groove characteristics

(2) StayCool Shallow-Concave PDC Cutter

PDC compacts are highly sensitive to temperature. Excessive heat can cause graphitization of the PDC layer, leading to cutter failure and reduced Rate of Penetration (ROP). In the early 2000s, Baker Hughes addressed this issue by introducing a shallow concave groove on the cutter face, designating it as the "Concave Cutter," as shown in Figure 2.

This design features a thicker diamond layer and generates larger cuttings during scraping. These characteristics contribute to its superior strength and impact resistance, enabling it to withstand severe dynamic loads when drilling hard formations. Field applications in the hard limestone and sandstone of the Woodford shale in Oklahoma demonstrated a performance improvement of approximately 10% in ROP and 37% in cumulative footage drilled.

Furthermore, the shallow concave geometry significantly enhances the overall hydraulic efficiency of the bit. Downhole tests confirmed that this cutter design reduces frictional heat generation at the rock-cutter interface by about 20% during drilling.

Fig 2. Concave Cutter shallow groove cutting cutter

(3) Stinger Center Cone Cutter

During the same period, Schlumberger introduced the Stinger center cone cutter, renowned for its high strength and exceptional wear resistance, as depicted in Figure 3. This cutter features a notably thicker polycrystalline diamond layer compared to conventional PDC cutters. Its geometry promotes stress concentration within the rock, facilitating preliminary rock failure by intensifying internal stresses.

The Stinger cutter is typically positioned in the center of the bit to enhance overall axial stability, thereby mitigating lateral vibrations and improving borehole quality. Furthermore, its distinctive conical shape aids in generating a localized crushing zone within the rock, which effectively initiates and propagates fractures [32].

Fig 3. Stinger cutter

(4) Axe Ridge Cutter

The Axe ridge cutter, illustrated in Figure 4, employs a unique axe-blade-like structure on its cutting face. This design allows the "axe blade" to penetrate the rock via concentrated point loading, effectively combining mechanisms of shearing, crushing, point loading, and plowing.

This cutter type incorporates a proprietary formulation of diamond granules, which enhances the impact resistance of the PDC layer. Furthermore, the PDC layer at the axe-blade edge is significantly thickened. These features collectively contribute to its superior performance, characterized by high efficiency, exceptional wear resistance, and improved impact strength.

Field performance of the Axelabde bit, equipped with Axe ridge cutters, was demonstrated in the Anadarko Basin—a formation dominated by shale with interbedded hard sandstone and limestone. In a single run, the bit successfully drilled 953.72 meters, achieving a Rate of Penetration (ROP) of 29.1 m/h. This represents a 27% increase in ROP compared to conventional PDC bits used in offset wells, while also reducing torque by 20% and saving approximately 14.75 hours of rig operation time [33].

Fig 4. Axe ridge teeth and Axelblade drill bits

3.2. Foreign Non Planar PDC Cutter

(1) Plowing-Type PDC Cutter

Significant research has also been conducted domestically on bit technology for hard and highly abrasive formations. In parallel, companies such as Haimingrun have introduced their own PDC products and proprietary technologies. A notable example is Haimingrun's plowing-type PDC cutter [34] (see Figure 5).

Fig 5. Plowing type diamond composite drilling teeth

(2) Multi-bladed, Non-planar PDC Cutter

Similarly, SF Diamond has conducted research targeting hard and highly abrasive formations, leading to the development of its multi-bladed, non-planar polycrystalline diamond compact cutter [35] (see Figure 6).

This cutter design significantly enhances drilling stability. It features a relatively simple structure, high material utilization, and low cutting resistance, making it suitable for drilling complex hard rock formations. Furthermore, it exhibits high impact resistance, which helps mitigate or prevent cutter chipping and spalling. These combined characteristics contribute to a notable improvement in the overall drilling efficiency of diamond bits equipped with this non-planar PDC cutter.

Fig 6. Polycrystalline diamond composite with multi blade irregular structure

(3) Trident Non-planar Cutter (Triangular Cutter)

The Trident non-planar PDC cutter [36], developed by the China Petrochemical Corporation (Sinopec Group), incorporates a convex ridge structure with three ridges spaced at 120-degree intervals. The cutter surface undergoes a de-cobalt treatment, effectively enhancing its impact resistance and wear durability (see Figure 7).

During drilling operations, the robust ridges—exhibiting superior impact resistance—first engage with gravel-bearing sections, fracturing the formation rock efficiently. This design helps prevent premature cutter damage and extends bit service life. Field application in the Long 17 well demonstrated the performance of a bit equipped with Trident cutters, achieving an average Rate of Penetration (ROP) of 1.55 m/h and a cumulative footage of 334 meters per bit. Compared to conventional PDC bits, these results represent a 49% improvement in average ROP and a 234% increase in average footage drilled per bit, indicating substantial enhancements in both drilling speed and bit longevity.

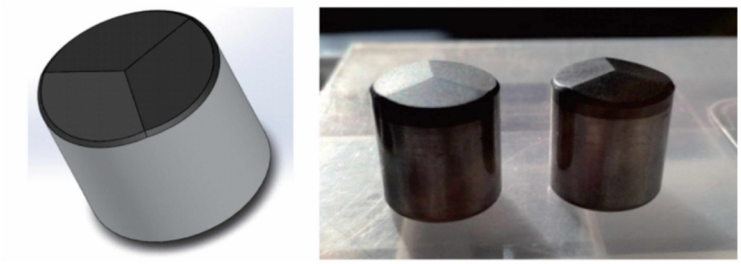

Fig 7. Trident non planar cutter

4. RESEARCH METHODS FOR NON PLANAR PDC TEETH

Currently, the rock fragmentation mechanisms of non-planar cutters are not fully understood, and knowledge regarding the characteristics of non-conventional cutters remains insufficient. Most research efforts remain largely empirical. Consequently, to design high-performance, customized non-planar cutters, the prevailing approach involves analyzing the rock-breaking mechanisms of common non-planar PDC cutters. Based on establishing evaluation metrics for single-cutter cutting performance, and by integrating the advantages of existing designs, the geometric features suitable for non-planar cutters in specific formations are inferred, leading to a preliminary conceptual outline.

Following this initial conceptualization, rock fragmentation simulations are performed on several promising non-planar cutter designs for evaluation. The optimal candidate is selected through a comparative analysis focusing on three key aspects: the characteristics of stress distribution, the magnitude and fluctuation of cutting forces (triaxial forces), and the specific energy of rock fragmentation.

Finally, the rock-breaking performance of the new cutter is compared against that of conventional PDC bits. Laboratory single-cutter tests are conducted to measure the triaxial force profiles during cutting and to analyze the cutting characteristics. Cutting efficiency is assessed by collecting and measuring the volume of cuttings generated per single scraping pass. Furthermore, comprehensive simulation analysis is carried out using established rock and full-scale bit models. This involves comparing the stress field distribution within the rock, as well as analyzing the bit's acceleration, torque, and angular velocity displacement.

4.1. Analysis of PDC Tooth Rock Breaking Mechanism

The primary objective of researching rock fragmentation mechanisms is to elucidate the influence of geometric parameters of PDC cutters, bit geometry, and drilling parameters on rock breakage patterns. This understanding facilitates the optimization of PDC cutter structural design, ultimately enhancing the fragmentation efficiency of both the cutters and the bit. The main methodologies employed include:

(1) Linear Cutting Test

Several experimental setups are commonly used for linear cutting tests, including those modified from drilling and milling lathes, shapers, vertical milling machines, scraping and crushing devices, dedicated linear rock cutting apparatus, and scratch testers. The primary advantage of these methods lies in simplifying the complexities of the cutting process, offering the most direct approach for investigating fundamental rock cutting mechanisms. However, limitations include short cutting distances and an overly simplified experimental environment, restricting analysis to parameters with pronounced characteristics.

For instance, in a setup modified from a drilling and milling lathe, a flattened rock sample is secured on the worktable alongside a fixed PDC cutter. A predefined vertical force is applied via the lathe's pressure system to engage the cutter with the rock. As the motor drives the system, the PDC cutter penetrates the rock, creating a groove and enabling data collection. It is important to note that the "flattened" rock surface lacks a strict standard, inevitably introducing some error due to surface irregularity.

Setups based on modified drilling and milling machines offer advantages of simple operation, low cost, and minimal space requirements. They can achieve at least three key experimental objectives: A) Investigating the impact of different PDC cutter geometries on fragmentation efficiency; B) Studying the influence of parameters such as weight on bit, back rake angle, cutting speed, and depth of cut on cutter performance; C) Examining how rock properties affect the fragmentation efficiency of PDC cutters.

(2) Rotary Cutting Test

The implementation of single-cutter rotary cutting tests allows for a closer simulation of actual PDC bit drilling conditions. Based on cutting distance, these tests are categorized into two types: short-radius rotary cutting tests, which focus on studying the rock fragmentation mechanism of the PDC cutter itself over limited distances, and long-distance continuous cutting tests, designed to evaluate core cutter performance under conditions more closely resembling actual drilling.

An example is a single-cutter rotary test apparatus modified from a horizontal lathe, equipped with a triaxial dynamometer and data acquisition system. The PDC cutter is fixed onto a steel tool holder connected to the dynamometer, enabling real-time measurement of tangential and axial forces. A positioning mechanism allows radial and axial adjustment of the cutter, which is then locked in place. After positioning, the rotating cutter cuts an arc groove of preset depth on the rock face.

Vertical Turret Lathes (VTLs) are primarily used for long-distance continuous cutting tests. Results regarding PDC cutter wear resistance and thermal stability obtained from VTL tests correlate well

with field performance feedback. Currently, VTLs have become crucial equipment for evaluating both individual PDC cutter performance and the overall performance of new bit designs.

(3) PDC Single-Cutter Static Indentation Test

Static indentation tests for PDC cutters are mainly divided into two categories:

PDC Single-Cutter Rock Indentation Test: In this test, the PDC cutter is pressed into a rock sample, primarily to observe rock failure. Analyzing resulting cuttings and indentation depth helps characterize the cutter's rock-breaking effectiveness and reflects the rock's resistance to cutter intrusion.

PDC Single-Cutter Overload Test: This test aims to study the failure of the PDC cutter itself. High-hardness materials like cemented carbide or tool steel are used as targets. The test helps evaluate and characterize the toughness of the PDC cutter material.

These two methods are complementary: one investigates the cutter's effectiveness during rock cutting, while the other examines the intrinsic properties of the cutter material, together providing a vital basis for improving and optimizing PDC cutter design.

(4) Drop Hammer Impact Test

The drop hammer impact test is the most common method for evaluating the impact resistance of PDC cutters. A precisely controlled lifting mechanism raises a hammer of specific mass to a predetermined height. Releasing the hammer allows it to strike the sample under free fall, with the impact energy determined by the potential energy difference between the hammer's lower surface and the sample's upper surface. This setup simulates various impact loads experienced by PDC cutters during actual drilling operations.

(5) Full-Scale PDC Bit Test

Full-scale PDC bit tests involve drilling into various rock types under laboratory conditions that simulate downhole environments. The rock fragmentation characteristics of the PDC cutters are observed under different parameters. These tests serve as a critical link between theoretical research and field application, providing valuable experimental data for studying bit geometry, dynamics, kinematics, and rock fragmentation mechanics. Furthermore, they enable performance evaluation of PDC bits, offering a scientific basis for optimizing bit design.

5. SUMMARY

As the fundamental cutting unit of a PDC bit, the performance of the PDC cutter is a primary determinant of overall bit effectiveness. Beginning with an analysis of non-planar PDC cutters developed both domestically and internationally, this paper provides a concise overview of the current research status and developmental trends pertaining to non-planar cutters and the rock fragmentation mechanisms of PDC cutters.

Chapter 2 details representative and recently innovative non-planar PDC cutters from around the world. Starting from the initial concept of the non-planar interface, it sequentially introduces international designs such as the StayCool shallow-concave cutter, the Stinger center cone cutter, the ONYX 360° cutter, the Axe ridge cutter, the Hyperbolic cutter, the Stabilis reinforced cutter, and the TriForce ridged convex cutter. For domestic developments, it covers the plowing-type diamond compact cutter, the multi-bladed non-planar PDC cutter, the Trident non-planar cutter, the polygonal cutter, the novel arrowhead polygonal cutter, the saddle-shaped cutter, the ribbed non-planar PDC cutter, a multi-ridge PDC cutter for enhanced rock breaking, a specific diamond compact design, the non-conventional extended cutter, the bionic PDC cutter, the cutter biomimicking mole cricket claws, the corrugated bionic PDC cutter, and the non-smooth bionic PDC cutter. This review provides

essential guidance for understanding the characteristics and rock-breaking behaviour of non-planar cutters.

Chapter 3 focuses on the research methodologies for non-planar PDC cutters. Starting from understanding the fundamental rock fragmentation mechanism of PDC cutters, it employs numerical analysis, mechanical force analysis, and experimental testing on conventional non-planar cutters to deduce their operational principles and fragmentation mechanisms. This establishes a necessary foundation for subsequent development of novel, customized non-planar cutters. Finite Element Analysis (FEA) aids in the preliminary assessment of new non-planar designs, enabling the study of stress concentration patterns and distribution laws via stress contour plots. Analysis includes observing the cutting volume per test, characterizing the rock fragments produced, performing mechanical force analysis on the cutters, and investigating the variation patterns in the Specific Energy of different PDC cutters. The influence of various cutter characteristic parameters on rock breaking efficiency is also examined. Experimental work is integrated to validate and complement the finite element analysis.

While research on traditional PDC cutters is now relatively comprehensive, the evolving demands of oil and gas exploration render them increasingly inadequate. The transition from planar to non-planar cutter surfaces is therefore inevitable. However, current understanding of the rock fragmentation mechanisms for non-planar cutters remains limited, and research on the cutter-rock interaction is insufficient, necessitating persistent efforts from researchers.

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