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Research Status and Technological Development Trends of Hybrid Drill Bits

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Abstract

In petroleum drilling engineering, the drill bit is the primary rock-breaking tool, and its performance directly affects drilling cost and operational efficiency. As oil and gas exploration and development extend from shallow formations to deep and ultra-deep reservoirs as well as increasingly complex geological environments, challenges such as high rock hardness, strong abrasiveness, and poor drillability significantly increase the difficulty of rock breaking, placing higher demands on drill bit structural design and service reliability. The PDC–roller-cone hybrid drill bit combines the shearing rock-cutting mechanism of PDC cutters with the crushing action of roller cones, enabling higher rates of penetration, improved directional control capability, and longer service life in hard formations, highly abrasive formations, and directional drilling operations. Considering that the understanding of the rock-breaking mechanism and the theoretical basis for structural design of hybrid drill bits remain incomplete, this paper systematically reviews recent research progress and engineering applications in China and worldwide. The structural characteristics and operating principles of hybrid drill bits are analyzed, and the shear–impact coupled rock-breaking mechanism as well as typical failure modes are discussed. Furthermore, their performance advantages and limitations compared with conventional roller-cone bits and PDC bits are evaluated under practical drilling conditions. Based on these analyses, structural optimization strategies and future technological development directions are proposed to support the engineering application and further research of hybrid drill bits.

Keywords

Hybrid Drill Bit; Rock-breaking Mechanism; Failure Analysis; Mechanical Design.

1. Introduction

In recent years, with the increasing imbalance in the global supply–demand structure of petroleum and the gradual depletion of hydrocarbon resources in shallow formations, the proportion of deep and ultra-deep wells has continued to increase. Oil and gas exploration and development are progressively shifting toward deep reservoirs and unconventional resources such as tight oil and gas and shale oil and gas. As a result, the geological conditions encountered during drilling have become increasingly complex, and problems such as poor drillability and high abrasiveness of rocks have significantly restricted drilling efficiency [1]. Under such conditions, conventional PDC bits often exhibit low rock-breaking efficiency, which greatly increases the development cost of oil and gas fields [2]. Therefore, higher requirements have been placed on the optimization and design of drill bits. Developing new types of drill bits suitable for deep and hard formations has become a critical challenge that must be addressed in the process of deep oil and gas exploration and development in China.

From another perspective, drilling efficiency directly determines drilling costs. When drilling efficiency is doubled, the overall drilling cost can be reduced by approximately one quarter [3]. Therefore, improving drilling efficiency is a primary approach to reducing drilling costs, maximizing economic benefits, and achieving efficient production [4]. To reduce costs and improve efficiency, more effective rock-breaking tools must be developed. Under these circumstances, hybrid drill bits have emerged.

A hybrid drill bit is a drilling tool that integrates the characteristics and advantages of two or more different types of drill bits. It can adapt to a wider range of formation conditions and improve drilling efficiency. The design concept of hybrid drill bits is to combine the working mechanisms and structural features of different drill bits to overcome the performance limitations that single-type drill bits may encounter in specific formations.

In recent years, hybrid drill bit technology has developed rapidly. These bits can achieve efficient drilling in hard formations as well as interbedded formations with alternating hard and soft layers, and they have been increasingly applied in oil and gas drilling operations [5]. At present, hybrid rock-breaking technology has become an effective means of improving drilling speed and efficiency in oilfields worldwide. Various structural forms of hybrid drill bits have been developed [6], among which the PDC–roller-cone hybrid drill bit is currently the most mature and widely used in petroleum drilling. In China, PDC–roller-cone hybrid drill bits manufactured by Sinopec Oilfield Equipment Corporation have been successfully applied in several oil and gas fields [7], [8], [9]. In addition, dual-stage hybrid drill bits have also been investigated and tested through a series of laboratory studies and field experiments in China, achieving promising results [10].

2. Research Status of Hybrid Drill Bits

At present, the most mature and widely applied type of hybrid drill bit is the PDC–roller-cone hybrid drill bit. This section mainly reviews the research progress and engineering applications of PDC–roller-cone hybrid drill bits.

Since the 1930s, several countries have proposed hybrid drill bit designs combining roller-cone bits with drag bits or diamond bits. In 1930, the American engineer Floyd L. Scott invented the world's first roller-cone-drag hybrid drill bit. The prototype of this bit was essentially a simple combination of a fishtail drag bit and a roller-cone bit. However, due to the lack of systematic design theory and experimental investigation at that time, premature failure frequently occurred in the fishtail and blade sections of the hybrid bit, which adversely affected its rate of penetration and service life. Consequently, the design was considered impractical and did not receive further development at that time [11].

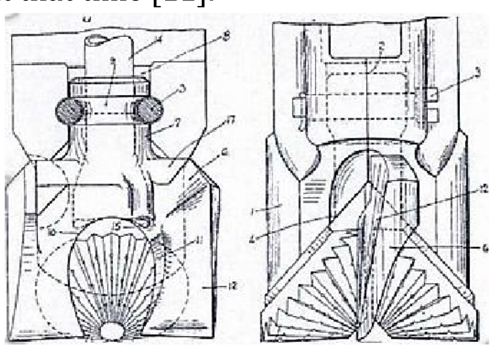

Fig 1. roller-cone–drag hybrid drill bit

In the 1980s, Smith International, Inc. and Reed Tool Company in the United States successively proposed patented technologies for roller-cone–diamond cutter hybrid drill bits. However, due

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to the limitations of polycrystalline diamond compact (PDC) material technology at that time, this concept did not achieve successful commercial application [12].

It was not until 2009 that Baker Hughes developed the Kymera series PDC–roller-cone hybrid drill bits [13]. These hybrid bits exhibit several advantages, including torque reduction, vibration mitigation, and slip suppression during drilling operations [14], [15]. They have been successfully applied in hard formations and interbedded formations in regions such as Canada, Saudi Arabia, Brazil, and China, demonstrating significant improvements in drilling efficiency [16]. Since their introduction, multiple types of Kymera PDC–roller-cone hybrid drill bits have been developed, and their directional drilling capability in carbonate formations and heterogeneous formations has been significantly improved [17].

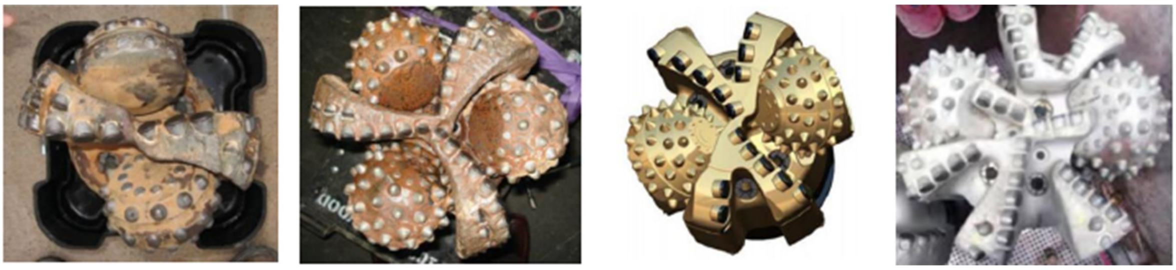

Fig 2. Kymera series PDC–roller-cone hybrid drill bits

In 2010, Baker Hughes reported the successful application of a roller-cone hybrid drill bit at a conference of drilling engineers in the United States. The hybrid drill bits developed in this study included configurations with two blades and two roller cones, as well as three blades and three roller cones. This type of hybrid drill bit can effectively mitigate bit balling and mud accumulation that commonly occur when conventional roller-cone bits drill in soft formations [18]. In addition, it can reduce stick–slip vibration and bit whirl typically observed during drilling with conventional PDC bits, thereby improving drilling stability [19]. Laboratory experiments and field tests indicate that this hybrid drill bit performs well when drilling soft plastic formations, hard formations, highly abrasive formations, and heterogeneous formations with hard interbeds [20]. The rate of penetration (ROP) achieved by this hybrid bit is 2–4 times higher than that of conventional roller-cone bits used in similar formations. In addition, the level of stick–slip vibration is approximately half of that observed with conventional PDC bits in comparable formations [21], and the occurrence of bit whirl is also significantly reduced, resulting in smoother and more stable drilling performance [22].

Fig 3. PDC–roller-cone hybrid drill bit used in field drilling operations

Subsequently, PDC–roller-cone hybrid drill bits achieved significant drilling footage records in oilfields across several countries and received widespread recognition in field applications. Field data indicate that PDC–roller-cone hybrid drill bits perform well in hard formations, heterogeneous interbedded formations, and highly abrasive formations, while also exhibiting relatively long service life. In directional wells, these hybrid drill bits can provide good

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inclination holding and build-up capability [23]. A PDC–roller-cone hybrid drill bit used in field drilling operations is shown in Fig. 3.

In 2011, researchers from Smith International were granted a U.S. patent on hybrid drill bit technology [24], presenting techniques for the design, simulation, optimization, and modeling of hybrid drill bits [25].

Following the introduction of the Kymera series PDC–roller-cone hybrid drill bits developed by Baker Hughes, research and development on PDC–roller-cone hybrid drill bits was rapidly initiated in China. On July 17, 2013, a PDC–roller-cone hybrid drill bit jointly developed by Southwest Petroleum University and the Drilling and Production Engineering Technology Research Institute of Chuanqing Drilling Engineering Co., Ltd., and manufactured by Baoji Petroleum Machinery Co., Ltd. (Chengdu Equipment Manufacturing Branch), was successfully tested in Well Ma 002-H1 in Sichuan Province. The PDC–roller-cone hybrid drill bit was designed to integrate the respective advantages of PDC bits and roller-cone bits. During drilling, the roller-cone cutting teeth first generate discontinuous indentation pits on the rock surface, producing a pre-fracturing effect. The PDC cutters subsequently shear the remaining fractured rock, forming a continuous crushed zone. Field tests showed that the operational stability of this hybrid drill bit was significantly improved compared with that of conventional PDC bits [26].

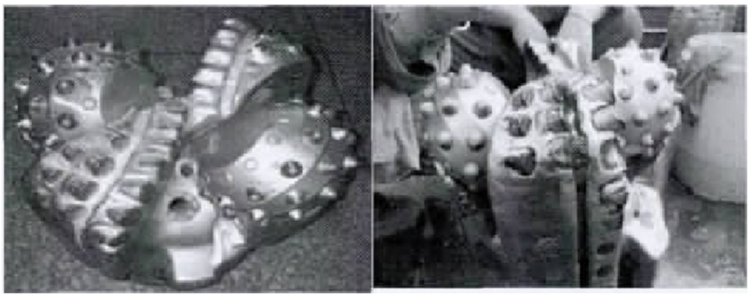

Fig 4. Field test of a Chinese-developed hybrid drill bit in Well Ma 002-H1, Sichuan, China

In the same year, Jianghan developed the KPM series PDC–roller-cone hybrid drill bits for the interbedded formations of the Xujiahe Formation in the Yuanba area [27], and conducted field tests in trial wells. The results showed that, compared with conventional roller-cone bits, the PDC–roller-cone hybrid drill bits achieved significantly higher rate of penetration (ROP) and greater drilling footage.

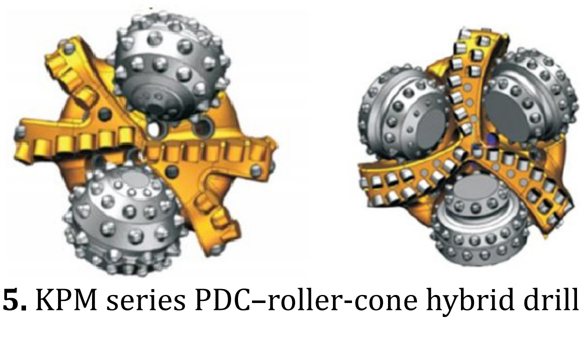

Fig 5. KPM series PDC–roller-cone hybrid drill bits

In 2017, Xia Shuang addressed the problems of multiple hard interbeds and poor drillability in the Xujiahe Formation of western Sichuan by conducting structural optimization design and hydraulic analysis of PDC–roller-cone hybrid drill bits [28]. Field tests were subsequently carried out in Well Yongsheng-1, achieving notable improvements in drilling efficiency.

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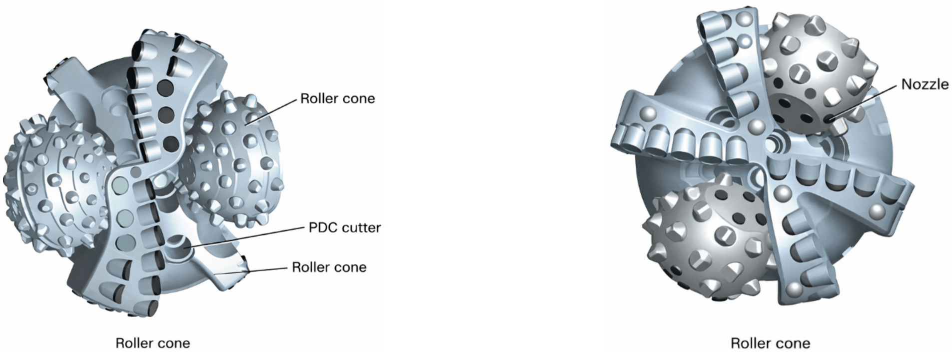
In the same year, the Jidong Oilfield Branch of PetroChina designed two structural configurations of PDC–roller-cone hybrid drill bits to address problems such as frictional resistance, weight transfer difficulty, and torque fluctuations during directional drilling in highly deviated wells in the Nanpu Oilfield. The two cutting structures consisted of 2 PDC blades + 2 roller cones and 4 PDC blades + 2 roller cones, respectively. Field tests were conducted in Well NP2-33 and Well NP5-28. The results showed that the application of PDC–roller-cone hybrid drill bits effectively alleviated problems such as severe weight transfer difficulty, large torque fluctuations, and difficulties in toolface control during directional drilling in highly deviated wells. Consequently, this technology provided a new approach for improving the rate of penetration (ROP) in directional sections of highly deviated wells [29].



(a) Hybrid drill bit with 2 roller cones and 2 PDC blades

(b) Hybrid drill bit with 4 PDC blades and 2 roller cones

Fig 6. PDC–roller-cone hybrid drill bits with two different cutting structures

In 2024, to address problems such as unstable drilling performance and impact failure of cutting elements, Yang Yingxin et al. proposed a new PDC–roller-cone hybrid drill bit with an independent buffering structure [30]. To mitigate the severe impact failure observed in conventional PDC bits when drilling the Ø311.2 mm interval of the Maokou Formation in the Sichuan Basin, a “3+3+3” configuration hybrid drill bit with an independent buffering structure was designed, consisting of three primary blades, three roller cones, and three independent buffering blades [31]. Field applications were subsequently conducted in the Maokou–Qixia Formations in the Sichuan–Chongqing shale gas block.

The results indicate that the independent buffering blades play a critical role in improving drilling stability. This design not only significantly enhances the service life of the drill bit, but also effectively improves the overall drilling efficiency in complex and hard-to-drill formations as well as structurally complex wells, thereby reducing the cost of oil and gas exploration and development.

Fig 7. “3+3+3” configuration hybrid drill bit with an independent buffering structure

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3. Development Trends of Hybrid Drill Bit Technology

Over the past decade, PDC–roller-cone hybrid drill bits have evolved into specialized and customized products designed for different formations and well types [32]. To more clearly illustrate the technological evolution of hybrid drill bits, several representative types are reviewed in this study, including early hybrid drill bits, formation-specific customized hybrid drill bits, innovative hobbing-type hybrid drill bits, and reinforced hybrid drill bits. These types correspond to several key stages in the development of hybrid drill bit technology: concept maturation, scenario-based customization, innovation in rock-breaking mechanisms, and enhancement of rock-breaking capability.

3.1. Early Hybrid Drill Bits: Peripheral Rolling-Cutter Hybrid Drill Bits

The engineering origin of modern PDC–roller-cone hybrid drill bits can be traced back to the new generation of peripheral rolling-cutter hybrid drill bits proposed around 2010. This type of bit is based on a mature PDC bit body, with rolling cutting elements arranged along the outer periphery, enabling fixed cutting and impact-induced rock breaking to act synergistically within a single bit. The design objective was to retain the high shearing efficiency of PDC cutters while using the rolling cutting elements to improve rock-breaking efficiency and drilling stability in plastic formations and complex well sections. Representative studies have shown that, in shale and other plastic formations, the rate of penetration (ROP) of this type of hybrid bit can reach 2-4 times that of conventional roller-cone bits [33]. In addition, the ROP exhibits a relatively good linear response to rotary speed, demonstrating dynamic characteristics that are clearly superior to those of traditional roller-cone bits.

Representative commercial products of this type of drill bit are generally classified as Kymera-type hybrid drill bits. According to relevant studies [34], their typical feature lies in the functional division between different cutting elements: the PDC primary cutting structure is responsible for the majority of volumetric rock removal, while the peripheral rolling elements provide auxiliary crushing, pre-fracturing, and stabilizing support. As a result, these hybrid bits are particularly suitable for shale formations, plastic formations, and interbedded formations with alternating hard and soft layers.This design concept established the fundamental technological framework for the subsequent development of hybrid drill bits over the following decades. Specifically, it achieves a balance between rock-breaking efficiency and drilling stability through the functional cooperation of different cutting elements, thereby laying the foundation for the continued evolution of hybrid drill bit technology.

3.2. Formation-Specific Customized Hybrid Drill Bits: Applications in the Marcellus Shale and the Tarim Basin

From the perspective of field applications, the true transition of PDC–roller-cone hybrid drill bits from laboratory research to industrial deployment was marked by their successful application in shale gas development and deep, complex formations. Among these cases, the hybrid drill bits used in the Marcellus Shale and the fixed-cutter–roller-cone hybrid drill bits applied in the Tarim Basin are particularly representative.

The Marcellus Shale gas field is one of the most important shale gas production regions in North America. Its unique geological characteristics require drill bits to achieve both high rates of penetration (ROP) and good borehole stability. In 2010, Baker Hughes reported an application case of a hybrid bit used in the Marcellus Shale, demonstrating that hybrid drill bits performed effectively under these formation conditions [35].

The Marcellus Shale typically consists of alternating hard and plastic layers, and stick–slip vibration frequently occurs during drilling, making conventional drill bits unsuitable for such conditions. The design concept of the hybrid drill bit is to combine PDC cutters with rolling cutting elements, enabling the bit to maintain a relatively high ROP in formations with high hardness and strong abrasiveness. At the same time, the rolling cutting elements help mitigate cutter chipping or breakage of PDC cutters, thereby improving drilling stability.

According to field reports, the hybrid drill bit achieved an approximately 30% increase in ROP compared with conventional roller-cone bits when drilling the surface sections of shale gas wells. The improvement in drilling performance was even more pronounced in interbedded formations with alternating soft and hard layers.

Meanwhile, in China, the application of hybrid drill bits in the Tarim Basin is also highly representative. The Tarim Basin is characterized by complex geological structures, where drilling intervals commonly contain alternating hard brittle rocks and softer formations, as well as strong formation heterogeneity, posing significant challenges to drilling operations. A study reported in 2014 indicated that the fixed-cutter–roller-cone hybrid drill bit developed for the Tarim Basin demonstrated excellent performance in highly heterogeneous and strongly abrasive formations through optimized hybrid structural design and rational arrangement of cutting elements [36].

According to field data, compared with conventional drill bits, this hybrid drill bit achieved an approximately 150% increase in the rate of penetration (ROP). In addition, it replaced the traditional drilling scheme that required multiple PDC bits and roller-cone bits, thereby significantly reducing the number of bit trips and the overall drilling time.

The key technical significance of this type of drill bit lies in the fact that hybrid drill bits are not limited to a single formation type. Instead, they exhibit more pronounced overall advantages in complex drilling intervals characterized by high abrasiveness, strong heterogeneity, and vibration-prone conditions. These successful applications have transformed hybrid drill bits from a theoretical concept into an effective engineering tool for improving drilling efficiency in complex formations.

3.3. Innovative Hobbing-Type Hybrid Drill Bits: Hobbing-Cone Hybrid PDC Bits

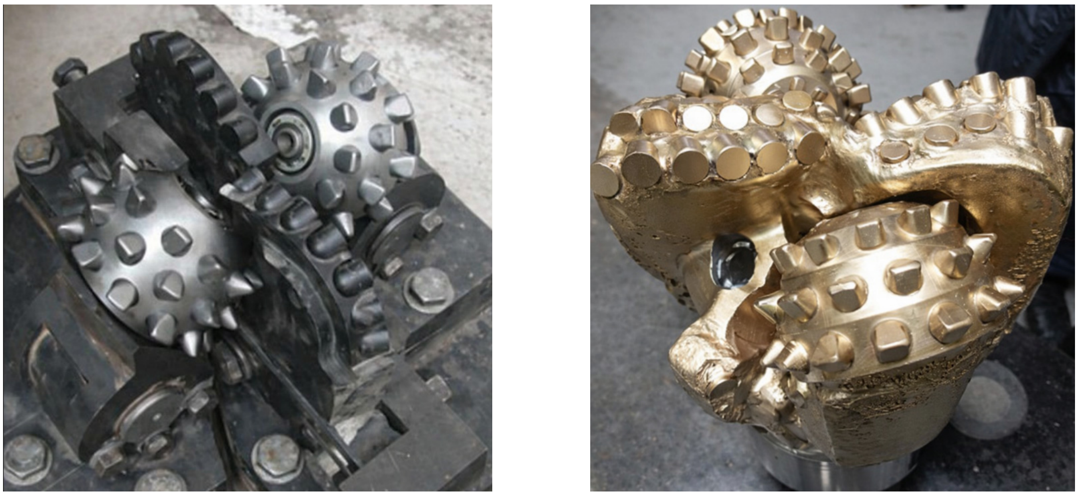

Fig 8. Hobbing-cone hybrid PDC drill bit

With continued technological development and innovation, hobbing-cone hybrid PDC bits have emerged as a new type of hybrid drill bit. Compared with early conventional hybrid bits assisted by roller cones, this type of bit is no longer limited to simple point-contact crushing. Instead, it introduces a hobbing-type cone structure, which forms groove-shaped crushed pits and crack zones at the bottom hole through a more continuous contact boundary, thereby enhancing the pre-fracturing and damage initiation capacity for hard and brittle rocks. A study published in 2023 reported that hobbing-cone hybrid PDC bits can improve the circumferential coverage at

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the bottom hole and strengthen the pre-fracturing effect, making them more suitable for hard and brittle formations than conventional hybrid bits.

The same study also provided relatively comprehensive experimental and field results. In soft rocks, the rate of penetration (ROP) of this type of bit may be approximately 20%–30% lower than that of conventional hybrid bits. However, in hard and brittle formations, its ROP can be 15%–20% higher. In field tests, the average ROP increased by 126.1%, while the cumulative drilling footage increased by 89.6%. These results indicate that the core advantage of hobbing-cone hybrid drill bits lies not in universal applicability, but rather in their targeted adaptability to deep, hard-brittle, and strongly heterogeneous formations.

From the perspective of technological development, hobbing-cone hybrid PDC drill bits represent the evolution of hybrid drill bits from a simple combination of fixed cutting and rolling elements toward a higher level of cooperative rock-breaking mechanisms. The design focus is no longer merely on increasing cutter aggressiveness or penetration capability, but rather on optimizing the functional interaction between the rolling elements and PDC cutters in terms of bottom-hole rock damage, thereby improving overall rock-breaking efficiency and drilling stability.

3.4. Reinforced Hybrid Drill Bits: PDC–roller-cone Hybrid Drill Bits with an Independent Buffering Structure

While hybrid drill bits have achieved higher drilling rates, they have also exposed new issues associated with their increasingly complex structures, particularly localized impact load concentration, uneven force distribution on rolling elements, and insufficient overall service life. To address these problems, a new generation of reinforced hybrid drill bits has recently emerged, represented by PDC–roller-cone hybrid drill bits with an independent buffering structure.A paper published in SPE Journal in 2025 reported a PDC–roller-cone hybrid drill bit equipped with an independent buffering structure [37]. The core design concept is to introduce an independent buffering load-bearing unit between the fixed cutting structure and the rolling cutting structure. This configuration reduces localized impact damage and mitigates the polygonal effect, thereby protecting the PDC cutters and improving the overall load transfer path within the drill bit [38].

Fig 9. Schematic diagram of a PDC–roller-cone hybrid drill bit with an independent buffering structure

The drill bit was experimentally evaluated and field-tested in the 215.9 mm directional well section of the Xujiahe Formation. The results showed that, during field application, the torque was significantly reduced [39], while both the single-run footage and the rate of penetration

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(ROP) were markedly improved compared with those of conventional PDC bits. The design of this drill bit was proposed on the basis of an analysis of impact-related failure, with the aim of mitigating the impact and vibration problems encountered by hybrid drill bits in complex formations [40]. These results indicate that the technical value of hybrid drill bits with an independent buffering structure lies primarily in their ability to further improve drilling stability and service life while retaining the advantages of hybrid rock-breaking. Accordingly, future technological competition in hybrid drill bits will no longer be limited to bottom-hole rock-breaking efficiency, but will increasingly focus on reliability-oriented engineering issues, including buffering, support, bearing performance, and load-transfer-path design.

4. Discussion on the Development Trends of Hybrid Drill Bits

Hybrid drill bits combine the impact–crushing rock-breaking mechanism of roller-cone bits with the shearing and scraping mechanism of PDC cutters within the same bottom-hole space. Although this coupling allows the complementary advantages of the two mechanisms to be utilized, it also significantly increases the complexity of the load distribution, contact conditions, and operational response of the drill bit [41]. Due to the particular structural characteristics of hybrid drill bits, there is often a relatively large spatial separation and substantial difference in rock-breaking modes between the roller cones and the fixed blades. As a result, the transition of bottom-hole loads between impact crushing and shear cutting is highly transient and discontinuous, which may lead to the superposition of impact loads and high-frequency vibrations. During this transition process, damage mechanisms such as PDC cutter chipping, cutter breakage, and abnormal wear can easily occur [42].

Therefore, the future development of hybrid drill bits will not simply rely on combining two rock-breaking mechanisms, but rather on achieving efficient cooperation and smooth transition between them. On the one hand, comprehensive structural optimization is required, including the coordinated layout of roller cones and blades, regulation of load distribution ratios, and optimization of spatial span and phase relationships, in order to reduce abrupt load variations and maintain a more stable load transfer process. On the other hand, improvements in PDC cutter materials and impact resistance are also necessary to enhance the damage tolerance of the cutters under the coupled effects of impact, thermal loads, and abrasion. In this way, improvements in service life can shift from passive wear resistance to reliability-oriented design. Only when both structural design and material performance are simultaneously optimized can hybrid drill bits achieve longer service life and more stable operational performance under complex drilling conditions.

In addition, the formation adaptability of hybrid drill bits still needs to be further enhanced. Existing studies and field applications have shown that hybrid drill bits can achieve favorable improvements in drilling efficiency in hard formations and interbedded intervals. However, difficult-to-drill formations in China are often characterized by hard–soft interbedding, abrupt changes in abrasiveness, and significant differences in drillability, making it difficult for a single set of structural parameters to cover all operating boundaries. Accordingly, a major development trend will be the implementation of formation-oriented customized and serialized design. Specifically, targeted configurations should be developed for different lithologic combinations, interbed proportions, abrasiveness levels, and section objectives, with systematic adjustment of parameters such as roller-cone penetration, PDC cutter density and back rake angle, hydraulic cleaning capacity, and impact-resistance redundancy. In this way, drill bit structures suitable for different application scenarios can be established, thereby expanding the applicability and adaptability of hybrid drill bits in various types of difficult-to-drill formations.

Hybrid drill bits must also satisfy the requirements of different drilling technologies and operational modes. Previous theoretical studies and field applications have shown that hybrid drill bits generally exhibit stable drilling performance and good toolface controllability. However, further design optimization is still required to keep pace with the continuous advancement of drilling technologies. In addition, the cutter layout design of hybrid drill bits can be further optimized to enable compatibility with intelligent drilling systems. Intelligentization has become a key trend in modern technological development, and the intelligent upgrading of oil and gas equipment is an especially important direction for future progress. By integrating monitoring systems into the cutter layout design of hybrid drill bits, it would be possible to detect operational parameters such as formation temperature, pressure, and torque, thereby enabling real-time sensing, control, and adjustment. Such integration would comprehensively improve the operational performance of hybrid drill bits during drilling. Therefore, cutter layout technologies compatible with intelligent hybrid drill bits will also constitute an important future development direction.

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