Research progress and development trends in polycrystalline diamond compact drill bits for oil and gas applications

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Polycrystalline diamond compact (PDC) drill bits are widely used in the oil, gas, and mining industries. Owing to their superior wear resistance and rapid penetration, PDC bits hold over 85% of the global market share and account for 90% of the footage drilled globally in oil and gas operations. However, their use is limited in challenging environments, including hard and abrasive rock formations. Therefore, enhancing their impact resistance and wear stability is essential for advancing PDC technology and expanding its applications.

Owing to its continuous and consistent carbon atom arrangement, natural polycrystalline diamond exhibits high hardness, wear resistance, and superior toughness compared with single-crystal diamond. The sintering process for producing PDC involves three stages: 1) cold compaction, where particles are compressed and rearranged; 2) cobalt infiltration, where molten cobalt dissolves graphitized carbon; and 3) liquid-phase sintering, where dissolved carbon reprecipitates, forming diamond-to-diamond bonds between particles.

PERFORMANCE IMPROVEMENT OF PDC CUTTERS

Optimization of raw materials and technology

Diamond powder size substantially influences PDC performance: finer powders increase hardness and wear resistance, but reduce impact toughness. Using mixed particle sizes improves compactness and reduces residual cobalt, enhancing overall performance. Furthermore, interface morphology has evolved from planar to complex configurations to mitigate residual stress with the impact resistance improving by 8.3% ~ 37.5%. An ideal binder requires excellent diamond wettability, low thermal expansion mismatch with diamond, and a low melting point.[1] The thermal expansion mismatch of cobalt with diamond and catalytic promotion of diamond graphitization at elevated temperatures limit the performance of these tools. Decobaltization of materials through acid leaching or electrolysis enhances thermal stability, but compromises impact toughness and flexural strength.

Geometric optimization

Planar-type PDC cutters can be modified by geometric alterations such as partial extension, resection, or combinatorial design, maintaining fundamental rock-breaking mechanisms of crushing and shearing.[2] Specific variants include the single-edge chamfered design that changes the geometry of the cutter-rock interaction from point-arc to ridge-line interaction, mitigating stress concentration while offering enhanced impact resistance and grinding efficiency.

Ridged-type PDC cutters function through engineered ridges that release localized stress concentration, which initiates rock breakage primarily via a combination of compressive and tensile failure. As the cutter moves through the formation, the sequential engagement of its cutting sides produces lateral thrust forces that induce directional rock splitting and displacement.

Conical-type PDC cutters are developed through parametric optimization of conventional conical geometries, employing tip compaction crushing and frontal tensile fracturing mechanisms.[3] These cutters are inherently limited in optimal rock fragmentation volume due to fundamental tip contact mechanics constraints.

Composite-type PDC cutters are designed to achieve synergistic rock fragmentation through the combined actions of crushing, tensile fracturing, and shear failure, exhibiting effects of plowing, scraping, and grinding actions. Such as those with saddle-shaped designs demonstrate superior cutting stability and wear resistance through coordinated compressive crushing, tensile crack propagation, and mixed tensile-shear failure mechanisms.[4]

Key technologies for PDC cutter performance improvement

Impact resistance enhancement is pursued through material advancements (nanoscale diamond integration, gradient structural designs, and novel binder systems), structural modifications (non-planar interfaces, multilayer composites, and 3D interlocking architectures), and processing innovations (HPHT parameter optimization, advanced sintering techniques, and post-treatment methodologies). Abrasion resistance improvement is achieved through the development and application of ultra-hard materials (such as high-purity diamond micro-powders and diamond-SiC composites), specialized surface treatments (such as CVD diamond coatings and ion implantation), and wear-resistant structural designs incorporating self-sharpening geometries and heterogeneous material distribution patterns. The high-performance PDC cutters processed via specialized techniques exhibit an average increase in impact resistance of up to 20%, an ultimate load improvement of 21%, and a reduction in wear rate by 64%.

ARRANGEMENT PARAMETERS OF VARIOUS KINDS OF PDC CUTTERS

Hybrid cutter placement technology, which involves the strategic alternating arrangements of multiple cutter specifications. For same-track cutting, maximizing WOB ensures adequate formation penetration while maintaining trailing cutter exposure within 0.6 mm of leaders to reduce specific energy consumption. Different-track cutting in PDC bits optimizes cutter density to leverage boundary effects, which can considerably reduce energy consumption and improve drilling efficiency. Researchers have identified the optimal different-track parameters for conical cutters preceding planar cutters (i.e., 18 mm spacing with 0.5 mm axial offset) and ridge-type cutters preceding planar cutters (i.e., 20 mm spacing with 0.75 mm axial offset).[5]

A systematic theoretical framework for globalized hybrid cutter arrangement remains underdeveloped, necessitating comprehensive research to establish optimized placement methods. We have proposed a high-efficiency hybrid layout methodology following section-specific performance criteria: efficient cutting in the inner cone, combined impact-wear resistance in the nose, abrasion resistance with cuttings removal in the outer cone, and gauge protection durability. Meanwhile, the final spatial arrangement is determined by installation angle, azimuth angle, back rake angle, and side rake angle interactions.

DESIGN AND OPTIMIZATION OF PDC BIT BEFORE APPLICATION

Traditional experimental testing methods using full-size PDC bits face challenges such as prohibitive costs, scalability constraints, and difficulties in accurately replicating true downhole conditions. Consequently, advanced numerical simulations with robust nonlinear contact capabilities have become the preferred methodology, enabling efficient and comprehensive performance analysis under realistic downhole environments.

Macroscopically, mathematical modeling and dynamic simulation of PDC bit rotation and rock cutting enables real-time monitoring of weight on bit, torque, and the rate of penetration. By targeting the reduction of weight fluctuation amplitude, average torque, and specific rock-breaking energy, this approach facilitates the optimization of crown profile design. Concurrently, hydraulic parameter optimization can be achieved through flow field and cuttings evacuation simulations that evaluate factors such as vortex formation and cuttings removal efficiency.

At the microscopic scale, Discrete Element Method (DEM) models rock discontinuities and dynamic interface evolution. Finite Element Method (FEM) characterizes rock constitutive laws and continuum-based multiphysics

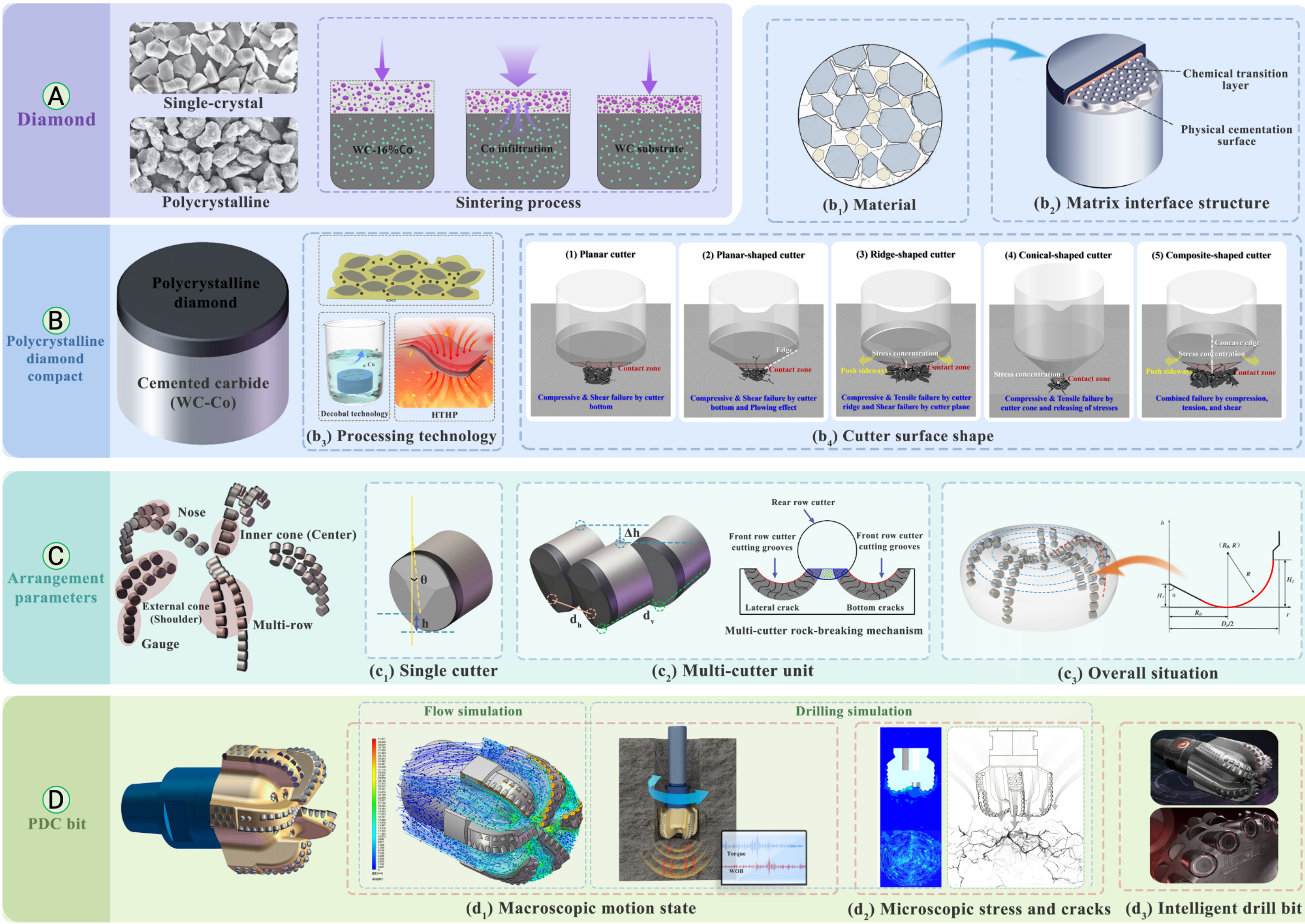

Figure 1. Research progress in PDC cutter and PDC drill bit technology

analysis. Computational Fluid Dynamics (CFD) simulates fluid behaviors like seepage and thermal convection. Comprehensive full-scale PDC bit simulations incorporating multi-field coupling conditions and rock fracture characteristics require further investigation.

RESEARCH DIRECTIONS AND DEVELOPMENT SUGGESTIONS

Based on the research progress in oil and gas PDC bit and PDC cutter technology, the following critical research directions are proposed to address the bottleneck challenges (such as significant challenges in PDC material innovation, limited efficiency gains from cutter layout optimization, and slow progress in bit intelligent upgrading) in PDC bit development:

1) implementing a multi-faceted technological approach encompassing material optimization, structural enhancement, and process innovation to comprehensively improve the thermal stability, wear resistance, and impact toughness of PDC cutters;

2) conducting fundamental research on rock-breaking mechanisms and performance characteristics of PDC cutters under in-situ thermomechanical and vibrational formation conditions, with quantitative evaluation of formation adaptability metrics;

3) establishing a holistic, customized, and intelligent hybrid-cutter drill bit with an adjustable unit to enhance its adaptation to complex formations by absorbing impact loads and minimizing the stick-slip and non-production time, such as through the use of a depth-of-cutting control unit in the Baker Hughes TerrAdapt adaptive drill bit and the design of the adjustable cutting blade in the NOV Smart-adaptive bit;

4) designing multi-functional drill bits with various sensors set inside them to collect the drilling parameters and in-situ formation properties, such as in the Halliburton Cere-bro Force™ drill bit, Schlumberger Synapse bit, and NOV BitIQ bit. By integrating intelligent perception and closed-loop control, intelligent drill bits can be used in conjunction with future drilling systems to optimize parameters in real time and actively adjust downhole conditions;

5) developing an integrated research framework combining customized PDC bit design with performance simulation, employing artificial intelligence methodologies to advance bit design optimization, such as in the Smith IDEAS system, Schlumberger Drillbench, and Halliburton DrillingXpert.

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DECLARATION OF INTERESTS

The authors declare no competing interests.