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MECHANICAL AND TRIBOLOGICAL PROPERTIES OF DRILLING TOOL BITS: A REVIEW

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ABSTRACT

Drill bits employed in oil and natural gas exploration operate under extremely harsh tribological environments characterized by high contact stresses, abrasive rock formations, elevated temperatures, corrosive drilling fluids, and cyclic impact loading. The performance, reliability, and service life of these drilling tools are largely governed by their mechanical and tribological characteristics. Therefore, the development and selection of drill bit materials require an optimal combination of high wear resistance, superior hardness, low coefficient of friction, excellent fracture toughness, thermal stability, and resistance to erosion and corrosion. Wear mechanisms such as abrasive wear, adhesive wear, erosive wear, thermal degradation, and fatigue-induced failure significantly influence drilling efficiency and operational costs. Advanced materials, including tungsten carbide composites, polycrystalline diamond compact cutters, thermally stable polycrystalline diamond, cubic boron nitride, and other superhard materials, have been extensively utilized to enhance performance under severe drilling conditions. This review summarizes the essential mechanical and tribological properties required for drill bits used in oil and gas exploration and discusses their influence on drilling efficiency, bit longevity, and failure prevention. Understanding these properties is important for the design and development of next-generation drilling tools capable of operating efficiently in increasingly demanding geological environments.

KEYWORDS drill bits; mechanical properties; tribological properties; friction; wear; corrosion resistance; PDC cutters; tungsten carbide.

1. Introduction

In oil and natural gas exploration, the reliability, availability and maintainability (RAM) of drilling equipment play an important role in increasing production and operational efficiency [1-4]. To achieve high RAM, it is necessary to reduce failures occurring during drilling and exploration. Common failures in drilling operations are closely associated with the mechanical and tribological behavior of drill bits [2].

Drill bits are among the most critical components in oil and natural gas exploration because they directly determine the rate of penetration, drilling cost, and operational efficiency. During drilling operations, drill bits experience severe environments involving high contact pressures, elevated temperatures, abrasive rock particles, impact loading, corrosion, and cyclic stresses. Consequently, the mechanical and tribological performance of drill bits significantly influences their service life and drilling economics.

The two major categories of drill bits used in the petroleum industry are roller cone drill bits and polycrystalline diamond compact (PDC) drill bits. It is important to identify the mechanical and tribological failures occurring in drill bits and to determine their causes and failure modes [3,4]. The critical properties required for drill bit materials include high hardness, high wear resistance, high fracture toughness, high thermal stability, excellent corrosion and erosion resistance, and high fatigue strength [5]. If any of these properties deteriorates during operation, the functional performance of drilling operations can be significantly affected [6-10].

This study provides a systematic review of the critical mechanical and tribological properties of materials used in drill bits for oil and gas exploration. Desired material properties for drill bit design and fabrication are discussed, and typical failure mechanisms observed during drilling are summarized with examples.

Figure 1. Typical drill bit configuration used in oil and natural gas exploration [7].

2. Results and Discussion

2.1. Mechanical Properties of Drill Bits

Mechanical properties such as hardness, strength, elasticity, fracture toughness, impact resistance and dimensional stability are key parameters for the design of mechanical components. Materials with higher and better-balanced values of these properties are generally more suitable for the design and fabrication of drill bits [11-14].

2.1.1. Hardness

Hardness is one of the most important mechanical properties governing the cutting efficiency and wear resistance of drill bits. Roller cone bits commonly employ tungsten carbide inserts with hardness values ranging from 1400 to 2200 HV, while PDC cutters utilize synthetic diamond layers with hardness values exceeding 7000 HV. The exceptional hardness of diamond enables PDC bits to drill abrasive and hard rock formations efficiently [11]. Representative values are summarized in Table 1.

2.1.2. Fracture Toughness

Although high hardness improves wear resistance, excessive brittleness may result in cutter failure. Therefore, fracture toughness is equally important for drill bit materials. Tungsten carbide-cobalt composites used in inserts provide a practical balance between hardness and toughness, whereas PDC cutters are engineered with optimized substrate and binder characteristics to enhance impact resistance and suppress crack propagation. As shown in Table 1, WC and PDC materials generally have lower fracture toughness values than carbon steel and high-speed steel, but their hardness and wear resistance are significantly higher.

2.1.3. Compressive Strength

Oil and gas drilling operations subject drill bits to high compressive loads that may reach several hundred megapascals. High compressive strength is essential to resist plastic deformation and maintain cutter geometry under severe drilling conditions. Synthetic diamond and tungsten carbide materials possess high compressive strength, making them suitable for deep-well and abrasive drilling applications. Representative values are given in Table 1.

2.1.4. Impact Strength

At the operational stage, drilling tools are subjected to shock loads and vibrations. Therefore, materials with better impact strength are preferred for the design and development of drill bits. Impact strength values may be obtained by Charpy, Izod or drop-blow testing, depending on the material and test standard.

2.1.5. Fatigue Resistance

Drill bits experience repeated loading cycles due to torsional vibration, stick-slip motion and bit whirl phenomena. These cyclic loads induce fatigue cracking, especially in the bit body and cutter-interface regions. Fatigue resistance is therefore essential for improving bit reliability and service life. In practice, fatigue performance depends strongly on material composition, heat treatment, microstructure, binder content, residual stresses and operating conditions.

2.1.6. Dimensional Stability

Downhole temperatures may exceed 250-350 °C in deep wells. Thermal degradation can soften binders, accelerate oxidation and reduce cutter integrity. Modern PDC cutters incorporate thermally stable diamond composites and improved substrate designs to enhance thermal resistance. Dimensional stability at high temperature is therefore a critical design requirement for drill bit materials.

Table 1.
Mechanical properties of materials used in drill bits.

Property	**Function in drilling**	**Representative values or target characteristics**
Hardness	Penetration of hard formations and resistance to abrasive wear	1400-2200 HV for tungsten carbide inserts; synthetic diamond >7000 HV
Fracture toughness	Prevention of cracking, chipping and cutter fracture	9-15 MPa·m^(1/2) for WC; 10-20 MPa·m^(1/2) for PDC; 50-150 MPa·m^(1/2) for carbon steel; 40-50 MPa·m^(1/2) for high-speed steel
Compressive strength	Resistance to crushing loads and preservation of cutter geometry	6-8 GPa for PDC; 3-5 GPa for WC; 3-4 GPa for HSS
Impact strength	Survival under shock, vibration and intermittent rock contact	Test-dependent; commonly assessed by Charpy/Izod or drop-blow methods
Fatigue resistance	Resistance to cyclic torsion, vibration, stick-slip motion and bit whirl	Material- and microstructure-dependent; high endurance limit is required
Dimensional stability	Maintenance of cutting geometry at elevated downhole temperature	Low thermal expansion is required; approximately (1-6)x10^-6 K^-1 for diamond/carbide-based systems

2.2. Tribological Properties of Drill Bits

Tribology is the science of friction, wear and lubrication. Tribological developments over the last few decades have contributed significantly to the improvement of mechanical-system RAM at the operational stage. In drilling, tribology plays an important role in reducing maintenance costs, improving penetration rate, limiting energy losses and extending tool life [3,15]. Desired tribological characteristics of drill bit materials are summarized below.

2.2.1. Abrasive Wear

Abrasive wear is the dominant wear mechanism in oil and gas drilling. Hard mineral particles such as quartz continuously scratch and plough cutting surfaces, causing gradual material removal. Tungsten carbide inserts and PDC cutters are specifically designed to minimize abrasive wear through high hardness and optimized microstructures.

2.2.2. Adhesive Wear

Under high contact pressures and temperatures, material transfer may occur between the cutter surface and rock formation, causing adhesive wear. This mechanism becomes more severe in sticky shale and clay formations, where rock fragments adhere to cutting surfaces and reduce drilling efficiency.

Table 2.
Tribological properties of materials used in drill bits.

Property	**Importance in drilling**	**Representative values or target characteristics**
High hardness	Reduction of abrasion, ploughing and plastic deformation	1400-2200 HV for tungsten carbide inserts; synthetic diamond >7000 HV
High wear resistance	Increase of RAM, bit life and drilling efficiency	Low wear coefficient is required; 10^-6-10^-7 order may be targeted in controlled laboratory conditions
Low coefficient of friction	Reduction of torque, heat generation, energy consumption and lubricant demand	Formation- and drilling-fluid-dependent; low and stable friction is preferred
Adhesive-wear resistance	Reduction of material transfer and bit balling in sticky formations	Strong surface integrity and suitable coatings/textures are required
Impact-wear resistance	Resistance to micro-chipping and intermittent contact with hard inclusions	High toughness and strong cutter-substrate bonding are required
Thermal-wear resistance	Prevention of binder softening, oxidation and diamond graphitization	Thermally stable PDC/TSP and efficient heat dissipation are preferred
Corrosion and erosion resistance	Resistance to chlorides, sulfides, abrasive particles and high-velocity drilling mud	Protective coatings, optimized binder systems and erosion-resistant geometries are required

2.2.3. Impact Wear and Chipping

Intermittent contact with hard inclusions and heterogeneous rock formations causes impact loading and micro-chipping of cutters. Roller cone bits are particularly vulnerable to insert fracture and tooth breakage, whereas PDC cutters may suffer edge chipping and delamination of the diamond layer.

2.2.4. Thermal Wear

Friction between cutters and rock generates substantial heat during drilling. Excessive temperatures can result in thermal softening of binders, oxidation of materials and graphitization of diamond layers in PDC cutters, ultimately reducing cutting efficiency and tool life.

2.2.5. Corrosive and Erosive Wear

Drilling fluids often contain chlorides, sulfides and abrasive particles that contribute to corrosive and erosive degradation of drill bit materials. Erosion is especially severe around nozzles and fluid channels where drilling mud velocities are high.

3. Factors Affecting Mechanical and Tribological Performance

Several operational parameters influence drill bit performance:

Weight on bit (WOB)
Rotary speed (RPM)
Drilling fluid composition
Formation hardness and abrasiveness
Temperature and pressure conditions
Cutter geometry and orientation
Vibration and stick-slip motion

Improper optimization of these parameters accelerates wear and shortens drill bit life. Materials commonly used for oil and gas drill bits combine these properties in different ways:

Tungsten carbide-cobalt (WC-Co): excellent hardness and wear resistance with good toughness.

Polycrystalline diamond compact (PDC): exceptional hardness and abrasion resistance for soft to medium-hard formations.

Thermally stable polycrystalline diamond (TSP): superior thermal stability and wear resistance.

Cubic boron nitride (CBN): high thermal stability and hardness for extreme environments.

For oil and gas drilling applications, the ideal drill bit material should simultaneously exhibit high hardness, high fracture toughness, excellent wear resistance, low friction coefficient, superior thermal stability, and strong corrosion and erosion resistance. Achieving an optimal balance between hardness and toughness is particularly critical because excessive hardness can reduce impact resistance, while excessive toughness may compromise wear resistance.

4. Surface Engineering Approaches for Performance Improvement

Recent research has focused on improving drill bit durability using advanced surface engineering technologies such as:

Nanostructured coatings
Diamond coatings
Ceramic coatings
Functionally graded materials
Laser surface texturing
Biomimetic surface engineering
High-entropy alloy coatings

These technologies can reduce friction coefficients, improve hardness and increase wear resistance under severe drilling conditions. Biomimetic textured surfaces have shown promising reductions in friction and wear in drilling-related applications. Surface engineering and analytical techniques also help identify abrasive grooves, oxidation products, crack initiation sites and microstructural degradation mechanisms.

5. Research Gaps and Future Directions

Current research indicates several important areas requiring further investigation:

Development of high-entropy alloy and nanocomposite coatings for drill bits.

Real-time monitoring of wear using machine learning and sensor technologies.

Improved thermal management of PDC cutters.

Tribological studies under high-pressure/high-temperature (HPHT) drilling conditions.

Integration of additive manufacturing for customized drill bit designs.

Multi-scale modeling of wear mechanisms using finite element and discrete element methods.

6. Conclusions

The mechanical and tribological properties of drill bits play a decisive role in determining drilling efficiency, operational cost and tool longevity in the oil and natural gas industry. High hardness, fracture toughness, compressive strength, fatigue resistance and thermal stability are essential mechanical properties, whereas resistance to abrasive, adhesive, erosive, corrosive, impact and thermal wear governs tribological performance.

Advances in material science, coatings, surface engineering and predictive wear modeling are expected to significantly improve future drill bit technologies and support deeper and more challenging drilling operations. A balanced combination of hardness, toughness, friction control, wear resistance and thermal stability should therefore be considered the primary design criterion for next-generation drill bits.

REFERENCES

1. Wang, X.; Ma, C.; Yang, G.; Zhang, S.; Zhang, Y.; Jiang, Z.; Yu, L.; Zhang, P. Preparation of molybdenum disulfide/bentonite nanohybrid and its tribological properties as lubricant for water-based drilling fluids. Tribology International, 2025, 202, 110309. https://doi.org/10.1016/j.triboint.2024.110309

2. Fato, D. A.; Rahmani, O. Enhancing drilling fluid properties using biodegradable waste additives: A comprehensive study on water- and oil-based systems. Journal of Environmental Management, 2024, 370, 123007. https://doi.org/10.1016/j.jenvman.2024.123007

3. Wani, M. F.; Gandhi, O. P. Development of maintainability index for mechanical systems. Reliability Engineering & System Safety, 1999, 65(3), 259-270. https://doi.org/10.1016/S0951-8320(99)00004-6

4. Ziyamukhamedov, J.; Wani, M. F.; Bhat, M. N. Tribological failure analysis of tungsten carbide tool inserts used in drilling operations. Journal of Failure Analysis and Prevention, 2025, 25(5), 2282-2289. https://doi.org/10.1007/s11668-025-02267-8

5. Macdonald, K. A.; Bjune, J. V. Failure analysis of drill strings. Engineering Failure Analysis, 2007, 14, 1641-1666. https://doi.org/10.1016/j.engfailanal.2006.11.073

6. Chen, C.; Li, C.; Reniers, G.; Yang, F. Safety and security of oil and gas pipeline transportation: A systematic analysis of research trends and future needs using WoS. Journal of Cleaner Production, 2021, 279, 123583. https://doi.org/10.1016/j.jclepro.2020.123583

7.Coherent Market Insights. Oilfield Drill Bits Market Size and Trends. https://www.coherentmarketinsights.com/market-insight/oilfield-drill-bits-market-999

8. Fang, H.; Duan, M. Offshore oil and gas drilling engineering and equipment. In: Offshore Operation Facilities: Equipment and Procedures. Elsevier, 2014, 141-340. https://doi.org/10.1016/B978-0-12-396977-4.00002-0

9. Lukawski, M. Z.; Anderson, B. J.; Augustine, C.; Capuano Jr., L. E.; Beckers, K. F.; Livesay, B.; Tester, J. W. Cost analysis of oil, gas, and geothermal well drilling. Journal of Petroleum Science and Engineering, 2014, 118, 1-14. https://doi.org/10.1016/j.petrol.2014.03.012

10. Fan, Y.; Huang, Z.; Gao, D.; Li, Q. Experimental study of an Al2O3/WC-Co nanocomposite based on a failure analysis of hammer bit. Engineering Failure Analysis, 2011, 18, 1351-1358. https://doi.org/10.1016/j.engfailanal.2011.03.028

11. Abbas, R. K. A review on the wear of oil drill bits: Conventional and state-of-the-art approaches for wear reduction and quantification. Engineering Failure Analysis, 2018, 90, 554-584. https://doi.org/10.1016/j.engfailanal.2018.03.026

12. Albdiry, M. T.; Al-Mensory, M. F. Failure analysis of drillstring in petroleum industry: A review. Engineering Failure Analysis, 2016, 65, 74-85. https://doi.org/10.1016/j.engfailanal.2016.03.014

13. Ropyak, L. Y.; Pryhorovska, T. O.; Levchuk, K. H. Analysis of materials and modern technologies for PDC drill bit manufacturing. Progress in Physics of Metals, 2020, 21(2), 274-301. https://doi.org/10.15407/ufm.21.02.274

14. Guo, Y.; et al. Advances in the application of biomimetic surface engineering in the oil and gas industry. Friction, 2019. https://doi.org/10.1007/s40544-019-0292-4

15. Guerrero-Martin, C. A.; et al. Tribology of drill bits in the geothermal industry: A literature review. Revista Fuentes: El Reventon Energetico, 2024, 22(1), 7-20. https://doi.org/10.18273/revfue.v22n1-20240018

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