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Recent Advances and Future Prospects in Bionic Impregnated Diamond Bit

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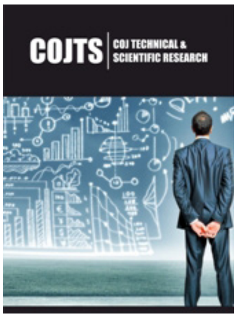

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Abstract

Drilling in complex structure faces challenges like low efficiency and rapid wear. The bionic impregnated diamond bit presents an effective solution, developed through a closed-loop process of simulation-driven bionic design, advanced manufacturing and rigorous field validation. This review synthesizes recent advances of bionic impregnated diamond bit, demonstrating that it significantly outperforms conventional bits in challenging structures, achieving substantial improvements in both rate of penetration and service life. Future development should focus on broadening biological inspiration, advancing manufacturing and integrating real-time monitoring for intelligent drilling systems.

Introduction

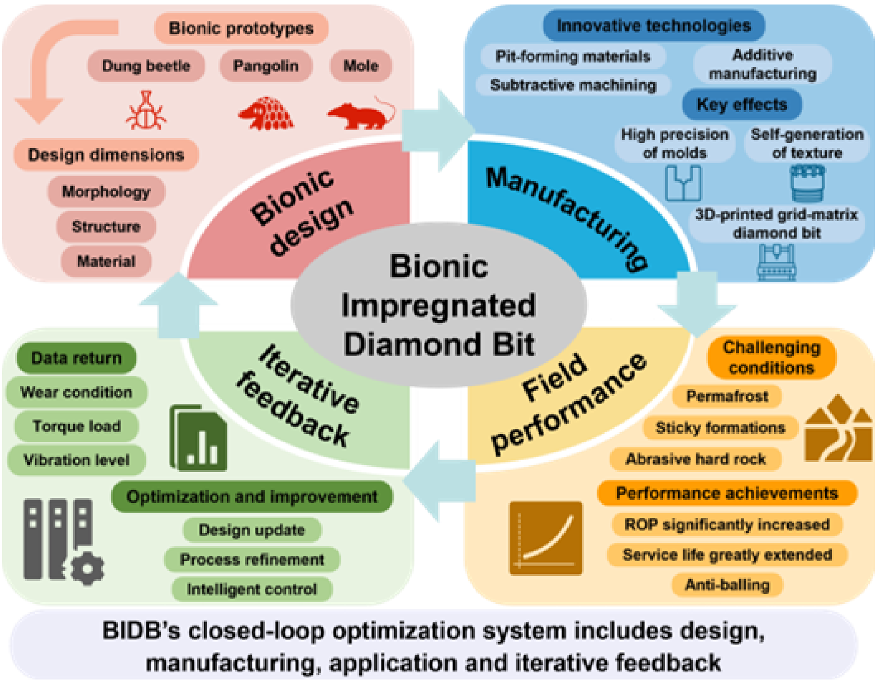

Figure 1: Closed-loop optimization system of BIDB.

The escalating demand for energy and resources makes their extraction ever more dependent on advances in drilling technology, which serves as an essential enabler in this domain. In recent years, drilling operations has been persistently challenged by complex conditions, including high temperatures, abrasive hard rocks and sticky structure [1]. As one of the core rock-breaking tools commonly used in drilling operations, the Impregnated Diamond Bit (IDB) plays a critical role. However, the IDB also exhibits drawbacks such as bit balling, a limited-service life and a low Rate of Penetration (ROP) [2]. Inspired by the exceptional anti-adhesion, wear resistance and digging efficiency of animals like dung beetle, pangolin and mole, Bionic Impregnated Diamond Bit (BIDB) was pioneered by Prof. Sun Youhong's team as an effective solution to above drilling challenges [3]. The BIDB has so far undergone experimental validation [4], progressively developed into a mature product and found broad use [5]. This review systematically presents recent advances in the design, manufacturing and performance of BIDB, while also providing an outlook on future development directions (Figure 1).

Bionic Design Optimization Driven by Numerical Simulation

The design of BIDB primarily encompasses three aspects: Morphology, structure and material. From a morphological standpoint, the introduction of non-smooth surfaces inspired by animals is a key strategy based on bionic non-smooth theory to improve anti adhesion and wear resistance [6]. In terms of structure, macro-scale advances that resemble animal claws include integrated "one-body" reinforcement structures that greatly increase the overall strength of high-matrix bits [7] and stepped/heterogeneous cutters that boost rock-breaking efficiency [2]. Regarding material composition, examples include sea urchin teeth-inspired self-sharpening composites [2,8] and shell inspired surface texturing of PDC for reduced friction and thermal wear [9]. Furthermore, numerical simulation especially Finite Element Analysis (FEA) is crucial in the structural design of BIDB. For instance, the development of BIDB has incorporated FEA for optimizing bionic structures, such as the reverse rotary torque self-balancing dual drill bit and the annular-grooved bit [10,11]. This simulation-driven approach enables the transition from intuitive biomimicry to the rational design of coupled systems. Subsequently, field operational data inform its iterative optimization.

Advanced Manufacturing of Complex Bionic Architectures

The fabrication of BIDB requires advanced manufacturing processes to translate intricate bionic designs into functional tools. Beyond conventional hot-pressing sintering, early innovation involved embedding specially formulated "pit-forming" materials within the matrix. During drilling, the preferential wear of these materials enables the self-generation and maintenance of non-smooth surface textures [6]. For structurally complex bits, several key manufacturing techniques have been developed. To produce molds with intricate features such as stepped cutters, integrated reinforcement ribs and gradually opening waterways, three-dimensional subtractive machining of graphite is employed to ensure high precision [12]. Additive manufacturing has also been explored to enable the fabrication of complex bionic bits, including a 3D printed grid matrix diamond bit and a functionally gradient diamond composite [13,14]. Furthermore, a uniform temperature sintering process tailored for large and complex bits improves matrix homogeneity and reduces energy consumption by more than 50% [15]. Complementing these fabrication methods, the uniform arrangement of diamond grits within the matrix further enhances bit stability and service life by ensuring consistent protrusion and even wear [16,17].

Field Application and performance Evaluation

The performance of BIDB has been rigorously validated through extensive field applications across diverse and challenging geological structures in China. Significant improvements in both service life and drilling efficiency have been consistently documented [18]. For instance, field tests conducted in drilling through granite at the Linglong gold mine in Shandong Province showed that BIDB increased ROP by 44% and extended service life by 74% compared to conventional bits [3,19]. In extremely cold and abrasive permafrost regions of Mohe, Heilongjiang Province, where the lithology is characterized by mudstone sandstone interbeds, bionic bits achieved a 22% higher ROP and a 73% longer service life compared to conventional bits [20]. Furthermore, the unique surface structures of BIDBs effectively mitigate bit-balling issues in soft, sticky structure by enhancing debris removal and maintaining cleaner cutting surfaces, a key factor in sustaining stable drilling parameters. These field results not only validate the potential of BIDB for challenging structures but also supply critical field data to guide iterative optimization.

Summary and Prospects

Above all, BIDB has established a mature, closed-loop development cycle of iterative optimization [1], encompassing bio-inspired design, advanced manufacturing and rigorous field validation [3,5,15]. Furthermore, BIDB has been successfully applied in extreme and complex geological settings, including hard rocks, permafrost regions and adhesive structure such as mudstone and shale, achieving significant performance improvements [19,20]. The future development of BIDBs should focus on three cutting-edge areas. First, inspiration should be drawn from a broader range of biological structures, such as claws, toes and carapaces, to develop innovative designs for new cutting teeth, integrated fluid channels and composite drill bit structures [21]. Second, advanced manufacturing technologies, particularly 3D printing and precision subtractive manufacturing processes [22], should be advanced to enable the low-cost, rapid and precise fabrication of complex BIDBs. Third, measurement technologies near the drill bit should be integrated into BIDBs to monitor real-time drilling parameters, thereby enabling adaptive control and further developing intelligent closed-loop drilling systems.

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