Jestr

Journal of Engineering Science and Technology Review 16 (2) (2023) 189 - 196

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Mechanism of Polycrystalline Diamond Compact and Diamond Impregnated Cutter Hybrid Bit Composite Rock Breaking

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Received 26 January 2023; Accepted 10 May 2023

Abstract

Rock breaking efficiency of drill bits is an important index for measuring the drilling efficiency in the oil and gas drilling field, and it is influenced by many factors, such as structure and material. This study developed a calculation model and an experimental model of rock breaking of polycrystalline diamond compact (PDC) and diamond impregnated cutter (DIC) hybrid bit to reveal the influence of bit structure and material on tangential force, axial force and wear height. On the basis of the calculation model of the co-rail arrangement of the PDC‑DIC hybrid bit and the rock breaking mode, a rock breaking mechanical parameter prediction model and a rock breaking performance test model were established. Rock stress calculation method, rock failure criterion, and mechanical specific energy (MSE) calculation method were used to analyze the rock stress and the relationship between MSE and tangential force, axial force, and wear height during combined rock breaking. The accuracy of the model was verified by experiments. Results show that the specific work of rock breaking of the PDC-DIC hybrid bit is less than that of PDC, and a reverse nonlinear relationship exists between specific work of rock breaking and wear height. The energy required for hybrid bit to break rock is less than that of PDC bit. A positive nonlinear relationship exists between the energy of PDC-DIC hybrid bit and the wear height, whereas the cutting depth and the wear height show a negative nonlinear relationship. The stress distribution of PDC rock breaking is uniform, and the maximum equivalent stress is up to 104 MPa. The stress distribution of rock breaking of the hybrid PDC-DIC is extremely nonuniform, and stress concentration occurs with a minimum equivalent stress of 84 MPa and a maximum stress of 161 MPa, which is beneficial to rock breaking. Rock breaking of PDC-DIC hybrid bit can promote the generation and development of rock cracks, thereby reducing the crushing strength of the rock. The study provides a design method and theoretical basis for designing a new type of PDC-DIC hybrid bit, with certain reference for exploring the rock breaking mechanism of various bits.

Keywords: Rock breaking efficiency; PDC; DIC; MSE; Rock breaking energy; Rock breaking stress; Rock ridge and groove

1. Introduction

Rock breaking efficiency is an important index for measuring the drilling efficiency in the oil and gas drilling field. A bit with high rock breaking efficiency is generally called a high-efficiency bit. Polycrystalline diamond compact (PDC) bit, which is widely used in the oil and gas drilling because of its high rock breaking efficiency, is considered to study high-efficiency bits [1]. The existing high-efficiency drilling bits are developed on the basis of PDC bits. According to different formation characteristics and drilling requirements, experts and scholars from different countries, such as China, the United States, Russia, and Britain, have developed high-efficiency PDC composite bits suitable for different rock types by adjusting the combination form of PDC bits, thereby optimizing and changing the structural parameters [2-5]. The categories of bits have been enriched, and the development of bit technology has been promoted [6-7].

The rock breaking principle is that the internal stress of rock reaches the rock breaking stress under the action of external force [8]. Many types of rocks are available, such as quartz sandstone, shale, and igneous rock; their abrasiveness and hardness vary [9]. Therefore, developing high-efficiency drilling bits with strong abrasiveness, high hardness, and poor drillability is still an urgent problem to be solved in the drilling development and petroleum engineering. At present, the structure and materials of high-efficiency and high-performance rock breaking bits have been widely studied in the field of petroleum engineering [10, 11], and the application effect is good. However, studies on rock breaking mechanism of bits are few, restricting the theoretical guidance for examining the structure of high-efficiency bits. Therefore, studying the rock breaking mechanism of composite bits is the key to improve the rock breaking efficiency and reduce the drilling cost.

Experts and scholars have been constantly improving the structure and material properties of drill bits and studying the rock breaking mechanism of different structures to achieve the best rock breaking effect [12-13]. The PDC-DIC hybrid bit, as a new type of bit, shows good rock breaking performance in the stratum with strong abrasiveness, high hardness, and poor drillability [14]. However, whether or not the bit achieves the best rock breaking effect must be determined in the study of hybrid PDC-DIC bit. Selecting the cutting tooth materials for hard strata and determining the layout mode and rock breaking mechanism of the bit cutting teeth can provide theoretical basis for developing bits with high rock breaking efficiency and good wear resistance, which is still an urgent problem to be solved in the drilling field.

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ISSN: 1791-2377
doi:10.25103/jestr.162.23

On the basis of these analyses, the interactive rock breaking mechanism of the PDC-DIC cutting element was examined, and a new type of hybrid bit was developed by carrying out experiments. The rock breaking process and mechanism of PDC-DIC cutting element and PDC-DIC hybrid bit were simulated using finite element software. The combined rock breaking experiment of the PDC-DIC hybrid bit cutting element was carried out on the test bench. The study results provide a design method and a theoretical basis for designing a novel PDC-DIC hybrid bit for hard stratum.

2. State of the art

At present, scholars in the fields of oil and gas exploration and bit development and processing have used various methods to develop PDC bits suitable for different formation types. Yachao Ma et al. studied the efficiency and service life of PDC bit to reduce the lateral force and proposed the corresponding optimization method to optimize the bit structure [2]. However, they did not develop a method for guiding the design of bit structure. Sun Yuanxiu et al. developed a hybrid cutting-ploughing bit to solve the problems of short service life and low penetration rate of conventional PDC bits in heterogeneous hard strata [3]. A hybrid cutting structure was formed, with PDC composite as the main component and tapered PDC bit as the secondary component, thereby improving the impact resistance and rock breaking efficiency of PDC bits in heterogeneous hard strata; a precedent was set for hybrid cutting meta-bits. This finding was only an experimental study result, but no theoretical improvement was found. Hocine Boussahaba et al. proposed a new PDC bit design method suitable for special stratum in northwest Kuwait; it innovated the bit layout structure and prolonged the service life [4]. This method was designed for special stratum in northwest Kuwait and was not universal. Huang Kuilin et al. put forward a modular rotary PDC bit and studied the changing law of cutting energy and MSE of cutting module under different structural parameters [5]. However, the rotary module of the PDC bit was unstable, and the service life was short. The problems of rock breaking principle and design principle were unsolved. Kuniyuki Miyazaki et al. studied the relationship between the rock breaking efficiency and the wear resistance of PDC bit in special stratum rock and drilling parameters through experiments, and then developed a method suitable for stratum lithology by changing drilling parameters, which can improve the rock breaking efficiency and reduce the wear rate [6]. The relationship between the performance and the structure and material of bits was not discussed. According to Wang Xiang et al. studying the rock breaking mechanism of PDC bit is greatly difficult because of its complex structure, where the rocks have different lithology and drilling conditions [7]. A 3D nonlinear dynamic simulation model of rock breaking by PDC bit was established using 3D CAD software and finite element software, and the rock breaking law of rocks with different lithology was studied. Moreover, a bit structure suitable for this rock was proposed, providing technical means for the subsequent study of bit-formation adaptability. Although this method is excellent for selecting bits, it cannot provide guidance for studying the rock breaking mechanism. Jinping Yu et al. conducted simulation and experimental studies of different cutter combination drills and proposed different cutter combination forms, all of which have lithology suitable for high-efficiency rock breaking. The viewpoint of using special drills with different combinations for rock breaking is provided, achieving higher efficiency and longer service life. Waleed Agawani, et al. designed a multifunctional bit, which has excellent impact resistance and is suitable for drilling heterogeneous carbonate formations, by combining PDC and tungsten carbide inserts [9]. The ROP is also higher than that of conventional bits. However, the design method and rock breaking mechanism are not presented in this study. Jinping Yu et al. studied the relationship between the performance of DIC and the material formula through indoor experiments and discussed the concept of rock breaking mechanism [10]. Some guiding suggestions were proposed for studying the rock breaking mechanism of hybrid bits. Ahmed Z. Mazen et al. studied the influence of factors, such as bit structure and rock properties, on the wear resistance of PDC bits and established a mathematical model to predict the wear resistance of PDC bits, which combined drilling parameters with bit wear for the first time [11]. Their study focused on the wear of bits rather than the combination design. Jinping Yu et al. analyzed the dynamic stress of rock during drilling and argued that the rock breaking stress is unchanged, but the dynamic stress produced by bits with different structures varies, influencing the rock breaking efficiency [12]. Studying the rock breaking mechanism from the perspective of bit structure is feasible. In addition to rock breaking efficiency, service life and wear resistance of bits should be considered. Rafid K. Abbas and Kanaan Mohammad Musa discussed the engineering requirements of personalized PDC bit for complex stratum structure and proposed to analyze PDC bit wear through infrared spectrum, combining the design of personalized bit with the study of rock breaking mechanism [13]. In A Novel Diamond Hybrid Bit Improved Performance in Hard and Abrasive Formations, Jinping Yu et al. showed a novel diamond hybrid bit, which can improve the bit performance in hard and wear-resistant strata. They suggested that the rock breaking mechanism of the bit should be further studied [14]. Rafid K. Abbas summarized the wear problems of oil bits and calculated the bit wear by simulation method, but the bit geometry structure and rock breaking mechanism were not described, as well as the design method and mechanism research [15]. Niu Shiwei et al. designed a disc-shaped hybrid bit to improve the drilling speed and service life of the bit in hard strata [16]. This bit has the advantages of conventional PDC bit and disc-shaped roller bit, and its key component is disc-shaped insert. Although the bit was studied through experimental method, the specific performance and the study process of the disc-shaped insert were not considered. Huang Kuilin et al. studied the relationship between impact speed and rock breaking efficiency of 360° rotatory teeth and disc PDC bit, especially introduced their structural characteristics and working principle, and simulated the rock breaking of the bit-rock coupling model [17]. This study introduced the idea of studying rock breaking mechanism, but did not discuss the study method. Yu Jinping et al. designed and applied the structure of PDC-DIC hybrid bit, which is suitable for hard and wear-resistant strata and has good application effect [18]. However, it lacks theoretical support for structural design. According to Carlos Galarraga et al., drilling deep wells is more conducive to the use of limited resources, and a drill bit with excellent performance is necessary in deep well drilling [19]. They are more interested in developing a special drill bit suitable for hard, abrasive, and thick conglomerate. The special drill bit has long service life and high penetration rate, which has been tested in practical engineering. However, because of technical confidentiality, the cutting structure of the drill bit, especially the rock breaking mechanism, cannot be explain.

These studies mainly proposed new ideas for the combination of different cutting elements of drilling bit, discussed the need for personalized bits in hard strata and the improvement of the wear resistance of bits [20]. Some scholars also put forward the concept of rock breaking mechanism and the design of personalized hybrid bits. However, few studies examine the rock-breaking mechanism of cutting elements with different structures through experiments and guide the design of bits based on experimental data. This study proposed a new method for designing PDC-DIC hybrid bits and analyzed the interaction rock breaking mechanism of PDC-DIC elements. Moreover, a DIC structure and test model and a rock breaking test model of PDC-DIC hybrid bits were established, and the experimental data of the DIC material were analyzed. The study results provide theoretical basis and experimental data for designing PDC-DIC hybrid bits suitable for hard stratum.

The remainder of this study is organized as follows. Section 3 analyzes the interactive rock breaking mechanism of PDC-DIC elements, establishes the DIC structure and test model, and determines the combined rock breaking test model of DIC-PDC hybrid bits. Section 4 determines the relationship between the cutting-edge structure of the PDC-DIC element and the rock stress, tangential force, axial force, and wears height by analyzing the test results of different structures of DIC. Section 5 summarizes this study and draws relevant conclusions.

3. Methodology

3.1 Physical model

The main design parameters of the SXXXH PDC－DIC hybrid bit: bit diameter 155.6 mm, gauge length 60 mm, 6 blades, 24 PDC, and 18 DIC. Fig. 1 shows the structural diagram of the PDC-DIC hybrid bit, Fig. 2 presents the physical photo, and Fig. 3 shows the structural diagram of DIC.

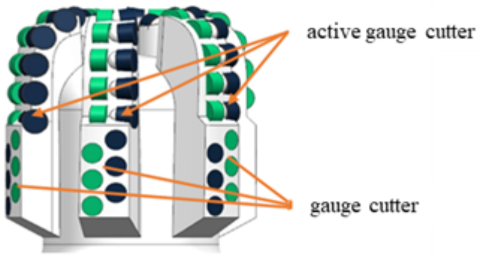


Fig. 1. Structural diagram of the PDC-DIC hybrid bit

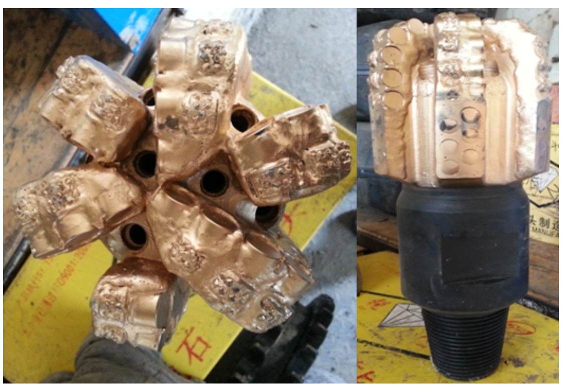


Fig. 2. Physical photo of the SXXXH PDC-DIC hybrid bit

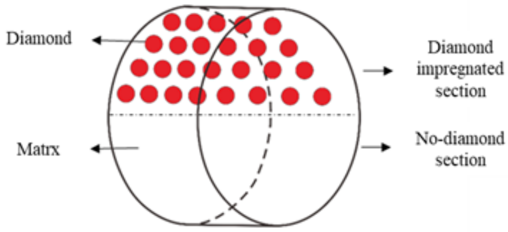


Fig. 3. Structural diagram of DIC

3.2 Modeling

Finite element calculation software was used to establish the geometric model of rock and combined cutting teeth, as shown in Fig. 4. In this model, the DIC breaks the rock initially with a back inclination angle of 0°, and then the PDC breaks the rock with a back inclination angle of 10°. The cutting depth of DIC is the exposed height of the diamond particles, and the cutting depth of the PDC is set to 1.0 mm. DIC and PDC are arranged on one side of the rock on the same track. The basic size of the model is as follows: .

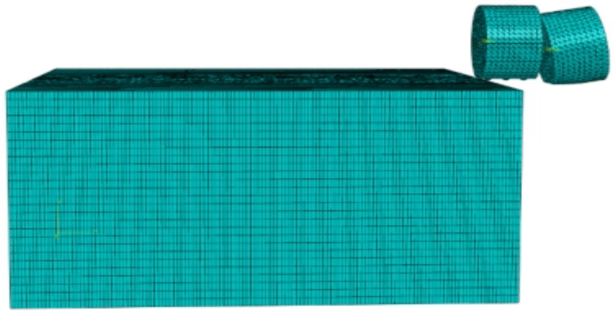


Fig. 4. Geometry of water jet propulsion pump

(1)PDC: the diameter of which is 16 mm, and the thickness is 10 mm.

Numerical simulation scheme: the back inclination angle is 10°, and the wear heights are 0, 0.5, 1, 1.5, 2, and 2.5 mm for the six types of PDC.

(2) DIC: the diameter of which is 16 mm, and the thickness is 10 mm.

Numerical simulation scheme: four types of DIC teeth with wear heights of 0.5, 1.0, 1.5, and 2.0 mm.

An exposed diamond particle model is established on the worn surface of DIC teeth. The structural parameters of diamond particles are diameter of 1.8 mm and diamond concentration of 100% (international standard 400%).

3.3 Calculation method and damage criterion

Rock is extremely complex and anisotropic, and it has nonlinear and anisotropic characteristics. Its deformation and failure are affected by many factors. In numerical simulation, the failure process of rock experiences three stages: elastic deformation, extremely short plastic deformation, and rock fracture [21].

3.3.1 Rock failure criteria

The failure form of rock is usually determined by the rock type and the surrounding environment. Scholars from China and foreign countries believe that the deformation of rock in the linear elastic stage satisfies the linear elastic deformation equation, and the failure criterion of rock in the triaxial stress state is satisfied when the rock is broken. Considering the microcracks in rocks, Drucker-Prager (D-P) criterion is generally used as the rock failure criterion in finite element numerical simulation calculation [22], as follows:

$$J_2^{\frac{1}{2}} = H + \alpha I_1 \tag{1}$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \tag{2}$$

$$J_2 = \frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{6} \tag{3}$$

where I_1 is the first invariant of stress tensor, J_2 is the first invariant of stress deviation, and α H represent the material parameters.

3.3.2 Rock damage criterion

In the rock breaking process of cutting teeth, when the plastic strain of rock reaches a certain value, the rock units are separated from the rock body. Based on the classical damage theory, the damage variable D is generally defined by elastic modulus, and the damage variables are as follows:

$$D = 1 - \frac{\tilde{E}}{E} = \begin{cases} 0 & (\varepsilon \le \varepsilon_0^{pl}) \\ 1 - \dfrac{\sigma}{\sigma_0} & (\varepsilon > \varepsilon_0^{pl}) \end{cases} \tag{4}$$

where E is the elastic modulus of the material without damage; $\tilde{E}$ is the macroscopic equivalent elastic modulus of rock when damage occurs; D is the material damage variable; σ_0 is the initial stress of the rock without damage; σ is the stress after the rock is damaged; ε is the plastic strain of rock; ε_0^{pl} is the equivalent plastic strain when damage occurs. When $D = 0$, the rock is not damaged. When $0 < D < 1$, the rock begins to be damaged. When $D = 1$, the rock unit is completely broken.

3.4 Calculation method of specific work of rock breaking

The rock breaking efficiency of a drill is an important index to study the rock breaking mechanism, and it is usually evaluated according to three parameters: tangential force, axial force, and specific work of rock breaking. The specific work of rock breaking refers to the work required to break the unit volume of rock, and the calculation method is as follows:

$$MSE_p = \frac{dW}{dV_{proj}} = \frac{f_\theta v_\theta + f_v v_v + f_r v_r}{S_{proj} v_\theta} \approx \frac{f_\theta}{S_{proj}} \tag{5}$$

where MSE_p is the specific work of rock breaking by the cutters, $\mathrm{J \cdot mm^{-3}}$; W is the work performed by the cutting teeth to break rocks, J; V_{proj} is the volume of the rock broken by the cutters, $\mathrm{mm^3}$; f_θ is the tangential force of the cutters, N; v_θ is the tangential velocity, $\mathrm{m \cdot s^{-1}}$; S_{proj} is the area of rock cut by the cutters, $\mathrm{mm^2}$.

3.5 Experimental verification model

On the basis of the rock breaking characteristics of the PDC-DIC hybrid bits, a rock-breaking performance test bench of the bit was used, as shown in Fig. 5. According to the actual situation of the drill bit, five bit pressure grades were set: 4, 8, 10, 12, and 15 kN. The bit was drilled at the speed of 57 rpm, and clean water was selected as the circulating cooling medium for drilling. The test bit model is shown in Fig. 6, and the rock model is shown in Fig. 7.

Fig. 5. Test bench of the rock breaking performance of bit

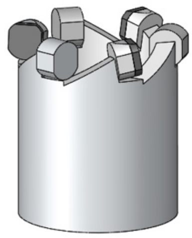


Fig. 6. Test bit model

Fig. 7. Granite samples

4. Result Analyses and Discussion

According to the results of the numerical simulation and theoretical analyses, the tangential force, axial force, and specific work of the PDC breaking rock are presented in Table 1. The tangential force, axial force, and specific work of rock breaking of the PDC-DIC hybrid bits are provided in Table 2.

Table 1. Numerical simulation results of the PDC breaking rock

PDC wear height /mm	Tangential force/N	Axial force/N	Cutting area/ $\mathrm{mm^2}$	Specific work of rock breaking/(J· $\mathrm{mm^{-3}}$)
0	732	517	5.35	0.1368
0.5	1265	989	8.82	0.1434
1.0	1664	1413	9.48	0.1755
1.5	2307	1932	10.78	0.2140
2.0	3163	2812	11.85	0.2669
2.5	4132	3768	12.74	0.3243

Table 2. Numerical simulation results of PDC and DIC breaking rock

Exposed height difference/mm	Combination number	PDC wear height/mm	DIC wear height/mm	Tangential force of PDC/N	Axial force of PDC/N	Cutting area of PDC / mm^2	MSE of PDC/($J \cdot mm^{-3}$)
0.5	D05P10	1.0	0.5	1534	1381	8.9	0.1724
	D10P15	1.5	1.0	1476	1362	8.6	0.1716
	D15P20	2.0	1.5	1834	1694	9.3103	0.1970
	D20P25	2.5	2.0	1982	1823	9.8297	0.2016
1.0	D05P15	1.5	0.5	2249	2015	10.2	0.2205
	D10P20	2.0	1.0	1963	1798	9.67	0.2022
	D15P25	2.5	1.5	2287	2032	10.2003	0.2242
1.5	D05P20	2.0	0.5	2918	2714	11.27	0.2589
	D10P25	2.5	1.0	2678	2487	10.56	0.2536
2.0	D05P25	2.5	0.5	3845	3612	12.16	0.3162

4.1 Relationship between specific work of rock breaking of PDC and tangential force, axial force, and wear height

The numerical simulation results of rock breaking by PDC are analyzed and theoretically calculated, and the relationship between the specific work of PDC and tangential force, axial force, and wear height is shown in Fig. 8. Under the same cutting depth, the rock-breaking work of PDC increases gradually with the increase in wear height, and the rock-breaking efficiency decreases nonlinearly. Under the same bit pressure, the bit depth of PDC into the rock gradually decreases. The MSE of PDC increases with the increase in the wear height.

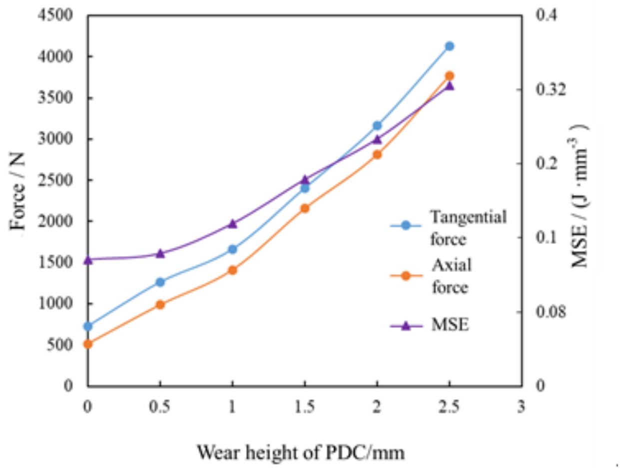


Fig. 8. Variation of tangential force, axial force, and MSE with wear height of PDC breaking rock

4.2 Relationship between the specific work of rock breaking of hybrid PDC-DIC and tangential force and axial force and its change law with the wear height

The rock breaking process of PDC-DIC hybrid bit under different wear height combinations is simulated, and the tangential force, axial force, and specific work of the rock breaking of PDC bit and PDC-DIC hybrid bit are compared and analyzed. Fig. 9 shows the tangential force of the rock breaking of PDC-DIC hybrid bit and PDC bit, Fig. 10 shows the axial force, and Fig. 11 shows the specific work of rock breaking.

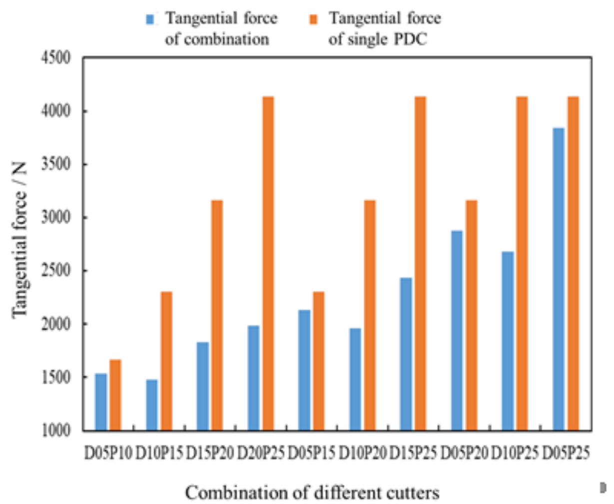


Fig. 9. Tangential force of PDC in PDC combined with DIC breaking rock and PDC breaking rock

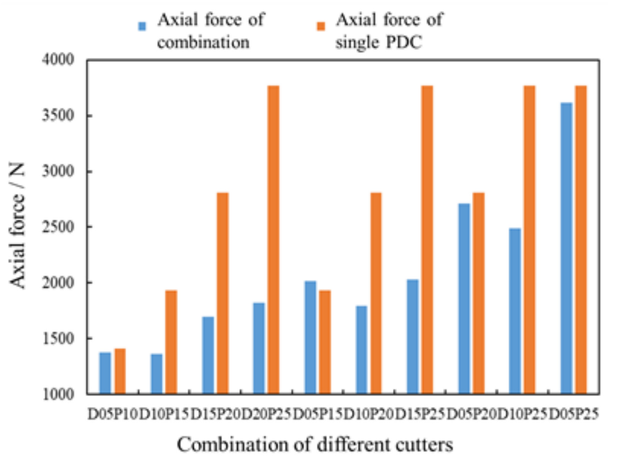


Fig. 10. Axial force of PDC in PDC combined with DIC breaking rock and PDC breaking rock

In Fig. 11, the MSE of the PDC-DIC hybrid bit is smaller than that of the PDC bit, indicating that the combined rock breaking process can reduce the MSE and improve the rock breaking efficiency of PDC bit.

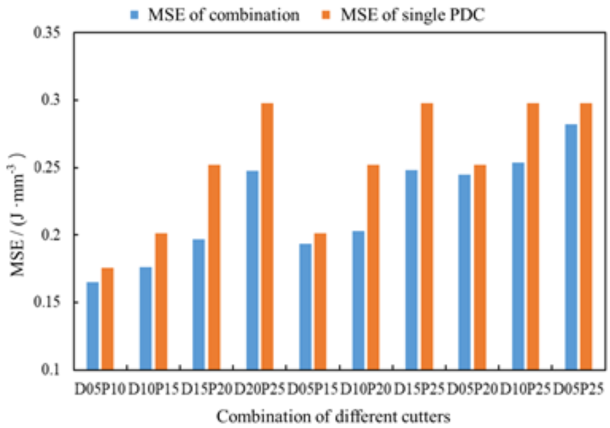
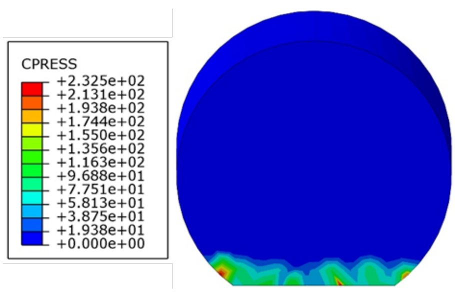


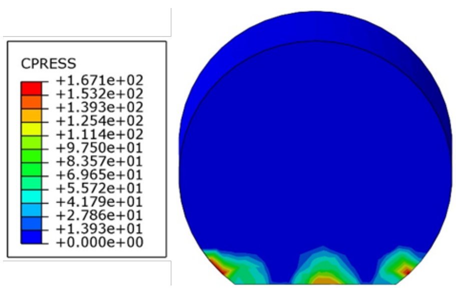
Fig. 11. MSE of PDC in PDC combined with DIC and PDC breaking rock

4.3 Analyses of rock breaking stress of PDC bit and PDC-DIC hybrid bit

Fig. 12 shows the contact stress of PDC bit during PDC combined with DIC and PDC single breaking rock. For rock breaking of the PDC bit, the contact stress is uniformly distributed at the bottom of the cutting teeth (Fig. 12(a)), and the maximum contact stress reaches 232 MPa. The distribution of contact stress is evidently uneven (Fig. 12(b)), and the maximum contact stress decreases to only 167 MPa due to the early damage of DIC to the rock. This finding demonstrates that the PDC bit requires less force to break the same rock, and it can break the rock more easily.



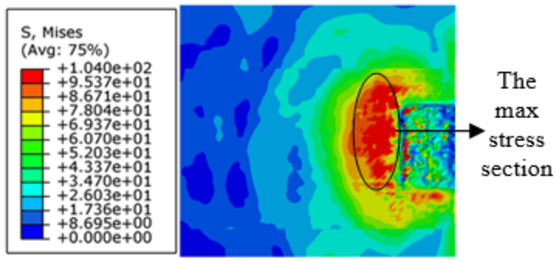
(a) PDC single breaking rock



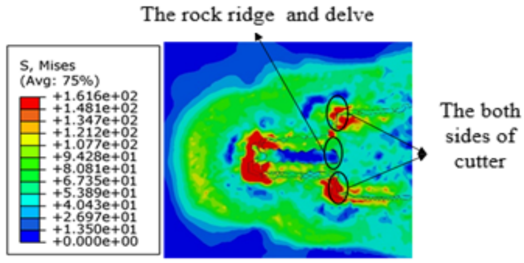
(b) PDC combined with DIC breaking rock

Fig. 12. Contact stress of PDC during PDC combined with DIC breaking rock and PDC single breaking rock

Fig. 13 presents the Mises stress of the rock during rock breaking. In the PDC single breaking rock, the stress distribution in the contact part of the rock is relatively uniform (Fig. 13(a)), and the maximum equivalent stress is 104 MPa. In the process of combined rock breaking, the stress distribution of the rock is extremely uneven (Fig. 13(b)), and the equivalent stress in the ridge and groove area is relatively small, at only 84 MPa. However, in the areas outside the ridge and groove, especially at the contact edge of the PDC bit, stress concentration occurs, and the equivalent stress is up to 161 MPa. Therefore, the rock is broken more easily.



(a) Mises stress nephogram of rock during PDC single breaking rock



(b) Mises stress nephogram of rock during PDC combined with DIC breaking rock

Fig. 13. Stress nephogram of rock during PDC combined with DIC breaking rock and PDC single breaking rock

4.4 Analyses of rock damage process during combined rock breaking

According to the stress analyses in Section 4.3, during the rock breaking of the PDC-DIC hybrid bits, the uniform distribution of the rock stress becomes concentrated, and its amplitude increases evidently. The PDC bit is more likely to break the rock after the DIC grinds the rock.

Fig. 14 shows the nephogram of the rock damage during the rock breaking of DIC, and Fig. 15 shows the nephogram of the rock breaking of diamond particles. The diamond particles break the rock, and a volume of destruction under high pressure is observed. A crack zone is formed under the diamond particles. The cracks develop and expand because of the tensile stress, forming macro-cracks, demonstrating that DIC damages the rock around the diamond and decreases the strength of the rock. This finding provides mechanical conditions for the worn PDC bit to drill into the rock continuously.

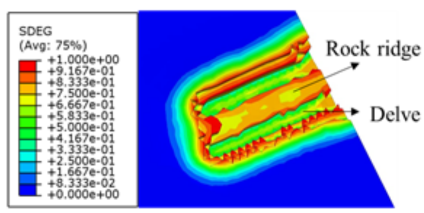


Fig. 14. Rock damage nephogram in the rock breaking process of DIC

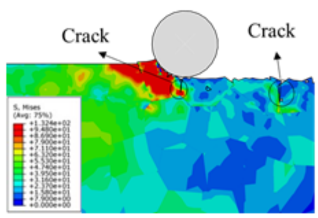


Fig. 15. Simulation of diamond breaking rock

5. Conclusions

This study established a physical model of PDC-DIC hybrid bits to explore the rock breaking mechanism of the PDC-DIC hybrid bits and reveal the relationship between force and wear height. The rock stress and rock damage process of PDC and PDC-DIC hybrid rock breaking were analyzed by numerical simulation and indoor bench test. The relationship among specific work of rock breaking, stress, and wear height was determined. The following conclusions are drawn:

(1) The specific work of rock breaking of PDC-DIC hybrid bits is less than that of PDC bit, and it is inversely nonlinear with the wear height.

(2) During the rock breaking of PDC-DIC hybrid bits, the rock breaking energy is less than that of PDC bit. The rock breaking energy of the PDC-DIC hybrid bits increases nonlinearly with the increase in wear height. Under the same bit pressure, the cutting depth shows an inverse nonlinear relationship with the wear height.

(3) The stress distribution is uniform during the rock breaking of the PDC bit, and the maximum equivalent stress reaches 104 MPa. When the PDC-DIC hybrid bits break the rock, ridges and grooves are formed on the rock surface, and the stress distribution is extremely uneven. The minimum equivalent stress is approximately 84 MPa, and the maximum stress is up to 161 MPa, which is beneficial to rock breaking.

(4) The combined rock breaking of the PDC-DIC hybrid bits promotes the development and generation of rock cracks and reduces the crushing strength of rock; thus, the rock can be broken more easily.

This study combined laboratory experiments, simulation calculation, and theoretical study to obtain the rock breaking law of the PDC-DIC hybrid bits. The established rock breaking model of the PDC-DIC hybrid bits is simpler and closer to the field practice, which has certain reference for further study of the rock breaking mechanism of various drills. Effective data of the actual failure process will be further collected and the model will be revised in the future study to enable the rock breaking mechanism of the PDC-DIC hybrid bits to satisfy the actual situation better given the lack of actual images demonstrating the failure process.

Acknowledgements
This work was supported by CNPC Key core technology research projects (No. 2022ZG06) and CNPC forward-looking fundamental strategic technology research projects (No. 2022DJ5503).

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