

Research Article

Experimental Study on the Materials and Performance of Diamond-impregnated Cutter**Yu Jinping¹, Zou Deyong^{1,*}, Wen Wu^{1,2} and Zhang Yin³**¹School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, 266580, China²Urban Construction Investment Management Center of Xishui, Huanggang 438200, China³Department of Petroleum Engineering, University of Alaska Fairbanks, Fairbanks, Alaska, 99775, United States

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Abstract

Rock-breaking efficiency and wear resistance of diamond-impregnated cutter (DIC) are important evaluation indexes of comprehensive rock-breaking performance. The comprehensive performance index of DIC is influenced by its composition and sintering method. A method for screening the material composition and testing the performance of DIC was proposed in this study to improve the rock-breaking efficiency and prolong service life of diamond-impregnated bit in hard stratum. In this method, through the establishment of the test model of DIC material, the performance of DIC prepared by different sintering methods were compared, and the DIC material suitable for hard formation was determined. Performance experiments were carried out to verify the rationality of calcining DIC with the addition of composite diamond particles with 60%WC+15%FeCuXP+25%CuSn as basic material. Results show that the DIC calcined via hot-pressing sintering demonstrates satisfactory wear resistance, high rock breaking efficiency, and long service life. Rate of penetration (ROP) and wear rate of single or composite grain size of DIC are positively correlated with diamond grain size. Small grain size indicates small ROP and wear rate. The comprehensive performance index of DIC with the single grain size is lower than that with composite grain size. The comprehensive performance index of the single grain size of DIC is only 0.91, while that of composite grain size of DIC reaches 0.96. This study can provide a theoretical reference for developing DIC with satisfactory wear resistance and high rock breaking efficiency.

Keywords: Diamond-impregnated cutter, Sintering, Rate of penetration, Wear resistance, Comprehensive performance

1. Introduction

Polycrystalline diamond compact (PDC) bits have been widely used in oil and gas drilling and development due to their satisfactory wear resistance and high rock breaking efficiency [1]. Bit manufacturers in countries, such as China, United States, and Canada, according to formation characteristics and drilling requirements, have developed different types of PDC bits with varying cutter shapes.

However, shallow surface oil and gas resources have become increasingly scarce with the continuous expansion of oil and gas exploration and development fields. Oil and gas resources in complex geological conditions and deep strata, such as shale gas and coalbed methane, have become important fields of land and sea exploration and development. Quartz sandstone, siliceous dolomite, and igneous rock, which demonstrate strong abrasiveness, high hardness, and poor drillability, exist in exploration and development projects of deep and ultradeep wells, such as shale gas and coalbed methane. Therefore, a diamond-impregnated bit suitable for such stratum is developed [2]. Developing a diamond-impregnated bit with strong wear resistance and high strength suitable for high-speed drilling in strong abrasive stratum is urgently necessary to develop high-efficiency diamond bits, improve rock breaking efficiency, and reduce cost.

Scholars in the field of bit development and production

have carried out various studies on bit cutters. Bits are mainly developed based on bit cutter structure and layout to improve their rock-breaking efficiency and prolong the drilling bit service life [3-6]. Although the rate of penetration (ROP) and wear resistance of bits are closely related to the structure and layout of cutters, the wear resistance, strength, and hardness of cutters are also influenced by their material composition and sintering mode. Selecting the cutter material, sintering mode, and test model plays a key role in the process of bit development. Therefore, the selection process of the diamond-impregnated cutter (DIC) material suitable for hard stratum, determination of the sintering method of DIC, and development of DIC with high rock breaking efficiency and satisfactory wear resistance are still urgent problems that must be solved in the field of bit development.

With the hardness, strength and compactness of DIC as evaluation indexes, the properties of DIC were tested, and the best matrix material and the most suitable sintering method were optimized. The wear resistance and rock breaking efficiency of DIC were tested using a test bench, and the mixture ratio of DIC matrix material formula and diamond grain size were determined to form a new DIC. The test results of the new DIC were compared and analyzed to select a suitable DIC for hard stratum. This study provides a design method and experimental basis for designing DICs suitable for hard formations.

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2. State of the Art

Different drill bits suitable for drilling hard strata are needed with the continuous expansion of the oil and gas exploration field. Scholars in the drill bit development industry have established PDC drill bits using different methods. Yu et al. [7] designed a new hybrid bit with PDC and DIC cutting unit to improve the rock-breaking efficiency, prolong the service life of PDC bit in hard ground with strong abrasiveness, remarkably improve the drilling efficiency, and reduce the drilling cost. This hybrid bit passed the field test verification, but the study process and method of the DIC material were not presented. Niu et al. [8] proposed a hybrid and disk-shaped hybrid drill bit to meet drilling requirements of hard strata. The key component of this drill bit is a disk-shaped insert that demonstrates comprehensive advantages of conventional PDC and disk-shaped roller cone bits. Although this drill bit was experimentally investigated, the study method of the disk-shaped insert was excluded. Kuniyuki et al. [9] experimentally explored the rock-breaking efficiency, wear resistance of PDC bits in special hard stratum rocks, and proposed the change of drilling parameters to adapt to stratum lithology, improve the rock-breaking efficiency, and reduce the wear rate. However, material properties and study methods of bit teeth were not discussed. Yu et al. [10] simulated and calculated rock dynamic stress during PDC bit drilling and investigated the relationship between the rock breaking process of PDC bit and bit structure from the mechanical perspective, but material properties of bit teeth were excluded. Kamatov et al. [11] pointed out that the composite bit is more effective for frequently interbedded bottom layers, such as deep shale, siltstone, limestone, and dolomite, using an engineering test but failed to present the specific structure of the composite bit. Alexis [12] argued that a hybrid drill bit is suitable for drilling in hard strata and combined PDC and cutting elements, such as diamond, to meet basic requirements for drilling in rock strata with high compressive strength, strong wear resistance, and low drillability; however, the material problem of the hybrid cutting element was ignored. He [13] proposed a finite element method to shorten the study period of the rock-breaking mechanism of personalized PDC bits and simulate the rock-breaking mechanism of personalized PDC bits combined with experiments and explored the rock-breaking process of tapered teeth of personalized PDC bits. However, this study focused on the influence of bit structure on bit wear and rock-breaking efficiency but ignored the composition of cutting elements. Agawani et al. [14] combined PDC and tungsten carbide inserts and designed a multifunctional drill bit with excellent impact resistance suitable for heterogeneous carbonate formations. Although tungsten carbide inserts were proposed, their components and screening methods were not discussed. Mazen et al. [15] and Yu [16] emphasized the importance of the bit structure. Mazen et al. [15] investigated the relationship between the bit structure, rock properties and PDC bit wear resistance and established a mathematical model for predicting the bit wear resistance. However, the study focused on bit wear and tooth material design. Yu [16] emphasized the rational layout of PDC and DIC cutting elements to improve the penetration rate and prolong the service life of drill bits. Although DIC was discussed, the composition of DIC was not mentioned. Abbas and Musa [17] argued that complex stratum structures need personalized PDC bits. The rationality and accuracy of infrared spectrum analysis of wear resistance of the PDC bit were proven via experiments.

The personalized bit design and rock breaking mechanism were combined, but the structure and composition of bit teeth were not discussed. Wang et al. [18] established a three-dimensional dynamic model of bit rock breaking, explored the rock breaking law, and designed the bit structure based on measured rock mechanical properties. However, the scholars failed to propose a design method for integrating multiple cutting elements. Saksala et al. [19] simulated rock breaking on a bit-rock coupling model and examined the relationship between impact velocity and rock breaking efficiency by combining numerical simulation and experimental approaches but failed to introduce cutting metamaterials and the study method. Abbas [20] reviewed wear problems of oil bits and calculated the wear loss via simulation. However, bit geometry and rock breaking mechanism were not described, let alone the material and method for designing bit teeth. Wang et al. [21] determined the tooth layout structure and mode of PDC bits in granite and hard sandstone interbedded formation through laboratory experiments, assessed the influence of the cutter layout structure on service life and penetration rate, and proposed the design method of PDC bit tooth structure. However, experimental basis and selection of cutting tooth materials were excluded. Galarraga et al. [22] emphasized the importance of developing special bits suitable for hard, abrasive, and thick conglomerate and sandstone intervals. Special bits were tested in practical projects. However, the bit structure, composition, and screening method of bit tooth materials were excluded because of technical confidentiality.

These studies proposed new viewpoints on PDC bit structure, cutter layout mode, and integration of cutting elements as well as discussed requirements for high strength and wear resistance of bits in hard stratum. Several investigations put forward the viewpoint of integration design of cutting elements. However, few studies have focused on screening DIC materials through experiments or determining the sintering method and composition of cutting elements based on experimental data. This study proposed a new method for developing DIC through experimental analysis and comparison. Basic requirements for the performance of DIC in hard stratum were analyzed. A matrix test model of DIC was established, and comparative analysis was carried out for test data of DICs with different diamond grain sizes. The results can provide an experimental basis for determining the sintering method of DIC, screening DIC materials, and designing DIC suitable for hard stratum.

The remainder of this study is organized as follows. Basic requirements of hard stratum for the DIC performance are analyzed, the matrix material formula and test model of DIC are established, the test model and calcination method of DIC materials are determined, and performance calculation and test methods of DIC are proposed in Section 3. The relationship between DIC and ROP and wear resistance of drill bit is obtained by analyzing the test results of DIC matrix materials and comparing test data of DICs with different diamond grain sizes in Section 4. Finally, the study is summarized and conclusions are drawn in Section 5.

3. Methodology

3.1 Pre-alloyed powder material formula of the DIC matrix

The two kinds of DIC matrix structure models are rectangular and circular cross-section matrix structure

models, as shown in Figs. 1(a) and 1(b), respectively. The two matrix structure models are used in different situations. The rectangular cross-section matrix structure is used to test and compare the matrix performance and the screen matrix material formula, while the circular cross-section matrix structure is utilized in the calcine-DIC to test and determine the rock-breaking efficiency of the DIC.



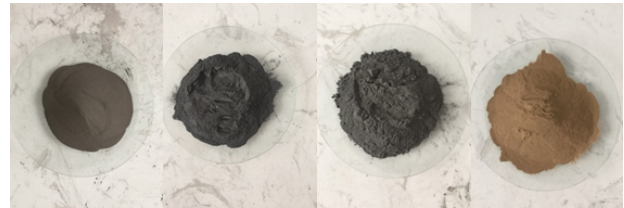
(a) Hexagonal matrix model, (b) Cylindrical matrix model
Fig. 1. Matrix models of the DIC

The DIC matrix performance should meet the following requirements: (1) high strength and hardness to ensure the service life of DIC when drilling hard strata, (2) satisfactory self-sharpening to expose diamonds continuously and maintain constant ROP of the diamond-impregnated bit during drilling, and (3) sufficient compactness and the better holding force between matrix and diamond to ensure that diamond particles will not easily fall off from the matrix.

Analysis of characteristics of metal carbide material (WC) demonstrated its high elastic modulus, hardness, and

wear resistance; satisfactory thermal conductivity and formability; and linear expansion coefficient close to that of the diamond. The WC material exhibits strong adaptive ability for hard ground with strong abrasiveness. The matrix formed by mixing and sintering WC as the basic material with copper- and iron-based binders can meet mechanical and rock-breaking properties of DIC.

Three kinds of iron-based binders, one kind of copper-based binder, and the WC material are mixed as the pre-alloyed powder of the DIC matrix material, as shown in Fig. 2. Figs. 2(a)–2(d) show the X6-600 pre-alloyed, YA321 pre-alloyed, FAM1031 pre-alloyed, and CuSn conventional alloy powders. Pre-alloyed powder components and their physical properties are listed in Tables 1 and 2, respectively.



(a) X6-600, (b) YA321, (c) FAM1031, (d) CuSn20
Fig. 2. Matrix models of the diamond-impregnated cutter

Table 1. Components of pre-alloyed powder

Pre-alloyed powder	Composition (percentage)
X6-600	Fe (62) Cu (11) Co (17) Sn (5) P (5)
YA321	Fe (64) Cu (16) Co (20)
FAM1031	Fe (80) Ni (18) Co (2)

Table 2. Performance of X6-600, YA321, and FAM1031

Pre-alloyed powder	Sintering temperature (°C)	Loose density (g/cm ³)	Theoretical density (g/cm ³)	Rockwell hardness (HRB)	Bending strength (MPa)	Oxygen content (%)
X6-600	780	≤3.0	7.87	100–110	1100–1400	≤0.23
YA321	800–880	3.0–3.4	8.2	100–105	1400–1700	≤0.28
FAM1031	720–920	2.1	8.05	88–91	900–1200	0.3–0.5

3.2 Matrix firing and mechanical analysis model of the diamond-impregnated cutter

By comparing the performance of DIC calcined by two different sintering methods, the cold-pressing sintering and hot-pressing sintering, the suitable sintering method was optimized.

The matrix structure in hot-pressing sintering is a hexahedron with a dimensions of 5 mm × 5 mm × 30 mm (Fig. 1[a]). The matrix mold and clamping tool are shown in Figs. 3(a) and 3(b), respectively, and the sintering furnace used for hot-pressing calcination is presented in Fig. 3(c).



(a) Graphite mold, (b) matrix fixture, (c) RJY2000A sintering machine
Fig. 3. Hot-pressing sintering mold and furnace

The matrix structure in cold-pressing sintering is a cylinder with a size of $\phi 16 \times 10$ mm (Fig. 1[b]). The matrix pressing mold, matrix sintering graphite mold, and sintering

furnace for sintering with cold pressing are illustrated in Figs. 4(a), 4(b), and 4(c), respectively.



(a) Matrix steel mold, (b) Graphite mold, (c) Vacuum sintering furnace
Fig. 4. Cold-pressing calcination model and sintering furnace

The powder of each component was first mixed for 8 hours, pressed and molded in a graphite grinding tool, and finally sintered in the RJY2000A sintering machine and vacuum sintering furnace in the process of matrix sintering.

Cold- and hot-pressing matrix sintering methods have different sintering processes.

The metal powder is molded by pressing at room temperature with a pressing pressure of 200 MPa in cold-pressing sintering. The matrix is sintered as follows: (1) Heating is applied from room temperature to 500 °C at a heating rate of 5 °C/minute. (2) The temperature is maintained for 1 hour to ensure that the vaporized plasticizer

can be fully discharged from the vacuum furnace. (3) The matrix is heated to the set sintering temperature at a heating rate of 10 °C/minute. (4) The temperature is maintained for 3 hours. (5) Heating is stopped and the matrix is cooled. The matrix is pressed and heated in the uniaxial direction in hot-pressing matrix sintering to ensure that molding and sintering are completed simultaneously.

Heating and pressing are carried out simultaneously in the hot-pressing sintering method. The thermoplastic state of the powder contributes to contact diffusion and flow mass transfer of particles. Therefore, the forming pressure is significantly lower than that of the cold-pressing method. Sintering parameters are set as follows: sintering temperature, 900 °C; sintering pressure, 30 MPa; and heat preservation, 5 minutes

Although the DIC matrix performance is related to the sintering temperature and pressure, the matrix composition plays a decisive role. WC is the main material and the alloy powder is composed of the metal binder and additive, which are fully mixed according to a certain proportion, in the formula of the matrix material of DIC (Table 3). The matrix is fired via cold- and hot-pressing sintering methods. Tables 3 list nine different matrix formulas and Table 4 lists the sintering parameters corresponding to each matrix formula. Different matrices can be obtained under different sintering methods and temperatures. Matrix formulas and sintering methods are screened via mechanical performance experiments and theoretical calculation

Table 3. Matrix formulas

Serial number	Matrix formula
1	60%WC+25%FeCuXP+15%CuSn
2	60%WC+20%FeCuXP+20%CuSn
3	60%WC+15%FeCuXP+25%CuSn
4	60%WC+25%FeCoCu+15%CuSn
5	60%WC+20%FeCoCu+20%CuSn
6	60%WC+15%FeCoCu+25%CuSn
7	60%WC+25%FeNiCo+15%CuSn
8	60%WC+20%FeNiCo+20%CuSn
9	60%WC+15%FeNiCo+25%CuSn

Table 4. Sintering parameters of each formula

Serial number	Sintering temperature (°C)	Sintering pressure (MPa)	Holding time (minute)
1	820, 860, 900, 940	30	5
2	820, 860, 900, 940		
3	820, 860, 900, 940		
4	860, 900, 940, 980		
5	860, 900, 940, 980		
6	820, 860, 900, 940		
7	820, 860, 900, 940		
8	860, 900, 940, 980		
9	860, 900, 940, 980		

The DIC matrix must demonstrate sufficient strength, hardness, compactness, and diamond holding power, which are related to the sintering method of the matrix formula, to ensure the excellent performance of the DIC. The matrix structure is a cuboid with a rectangular cross section to facilitate the matrix strength test. The bending strength of the matrix is calculated as follows:

$$\sigma_b = \frac{3PL}{2bh^2} \quad (1)$$

where

σ_b -bending strength, MPa;
 P -breaking load, N;
 L -fulcrum spacing, mm;
 b -sample width, mm; and
 h -sample height, mm.

The decline rate of the bending strength is used to reflect the holding force of the matrix on the diamond after measuring bending strengths of the matrix and DIC. The decline rate of the bending strength of the matrix is expressed as follows:

$$q = \frac{\sigma_b - \sigma_D}{\sigma_b} \quad (2)$$

where q -decline rate of the bending strength, %;

σ_b -bending strength of matrix without diamond particles, MPa;

σ_D -bending strength of matrix with diamond particles, MPa.

A Rockwell hardness tester HR150-DT was used to test the hardness of the matrix. The compactness of different formulas under different sintering processes was calculated as follows:

$$D = \frac{\rho}{\rho_0} \quad (3)$$

where D -compactness, %;

ρ -actual density, g/cm³;

ρ_0 -theoretical density, g/cm³.

The ratio of penetration rate to wear rate is a comprehensive performance index in engineering and an important index for evaluating the rock-breaking performance of DIC. A large comprehensive performance index indicates the improved rock-breaking performance of DIC. The comprehensive performance index of DIC is expressed as follows:

$$CPIOB = \frac{ROP}{ROW} \quad (4)$$

where $CPIOB$ -comprehensive performance index of bit, %;

ROP -rate of penetration, m/h;

ROW -rate of wear, g/s.

3.3 Models of diamond-impregnated cutters with different diamond grain sizes

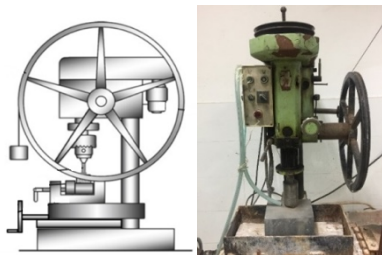
No. 3 material (60%WC+15%FeCuXP+25%CuSn) was selected as the matrix material formula of DIC, and the DIC was prepared via hot-pressing sintering method according to experiments of matrix sintering and mechanical properties. Based on the matrix material formula, various diamond particles were mixed thoroughly and then sintered into DIC models with different diamond grain sizes. Performance comparison experiments were carried out to analyze the performance of DIC with different diamond grain sizes and determine diamond parameters. Table 5 presents the formula of diamond parameters with different grain sizes.

Table 5. Diamond grain size parameters

	Serial number	Diamond parameters
Single grain size	1	100% concentration, 20/25 mesh
	2	100% concentration, 30/35 mesh
	3	100% concentration, 40/45 mesh
	4	100% concentration, 50/60 mesh
Composite grain size	1	20/25mesh (30%) +30/35mesh (40%) +40/45mesh (30%)
	2	20/25mesh (30%) +30/35mesh (40%) +50/60mesh (30%)
	3	20/25mesh (30%) +40/50mesh (40%) +50/60mesh (30%)
	4	40/50mesh (30%) +40/50mesh (40%) +50/60mesh (30%)

3.4 Experimental model of the diamond-impregnated cutter performance

The wear resistance, bending strength, holding force, and penetration rate of DIC are important performance evaluation indexes. The most direct performance evaluation method for DIC is test. The test model of DIC is shown in Fig. 5. The DIC hardness tester is presented in Fig. 6.

**Fig. 5.** Test model of performance of DIC**Fig. 6.** Hardness tester**Fig. 7.** ROP tester model

Figs. 7(a) and 7(b) show the penetration rate testing machine model and testing machine, respectively. A ROP testing machine was used to test and analyse the comprehensive performance of the DIC, screen the sintering method, and determine the formula of the DIC.

4 Result Analysis and Discussion

4.1 Analysis and determination of the matrix sintering method

In the comparative experiment of sintering, the No. 3 formula (60%WC+15%FeCuXP+25%CuSn) was selected as the DIC matrix. Table 6 lists the hardness and compactness of No. 3 matrix material when different sintering methods are used.

Analysis of the cold-pressing sintering method: The hardness and density of the matrix sintered via the cold-pressing method increase, with a maximum density of 82.3%, as the temperature rises. This finding indicated that the matrix sintering is incomplete and the metallurgy and alloying degree is low. The minimum hardness of 102.5 HRB fails to meet the requirement for the DIC hardness in hard stratum.

Analysis of the hot-pressing sintering method: The density of the matrix sintered via the hot-pressing method is 99.1%, which is close to the theoretical density of 100%. This finding indicated that the alloy powder can be completely alloyed and metallurgically sintered via hot pressing. The maximum hardness of the matrix sintered via the hot-pressing method is 48.4 HRC, which is significantly higher than that of the matrix sintered via cold pressing and meets the requirements for the DIC hardness in hard stratum.

The comparison results showed that the DIC matrix sintered via cold pressing can meet the requirements for hardness and compactness of the DIC in hard stratum better than that sintered via hot pressing.

Table 6. Comparison of hardness and compactness under different sintering methods

DIC sintered by cold-pressing			DIC sintered by hot-pressing		
Sintering temperature (°C)	Hardness (HRB)	Compactness (%)	Sintering temperature (°C)	Hardness (HRB)	Compactness (%)
900	66.8	70.1	900	48.4	99.1
940	75.3	74.4			
980	87.6	79.8			
1020	102.5	82.3			

4.2 Analysis of test results of the DIC matrix

Fig. 8 presents the comparison of the hardness of DIC and matrix of nine material formulas sintered by hot-pressing. Fig. 9 shows the bending strength of nine matrixes without diamond and DICs with diamond.

Although the hardness of matrix of No.3 material formula (60%WC+15%FeCuXP+25%CuSn) is not the

highest, the hardness of DIC is the highest. The DIC and the matrix sintered via hot-pressing sintering method demonstrate high hardness, but the decline rate of the bending strength of the matrix is the smallest, as shown in Fig. 10. Hence, No. 3 material (60%WC+15%FeCuXP+25%CuSn) formula is suitable for bedrock hard stratum.

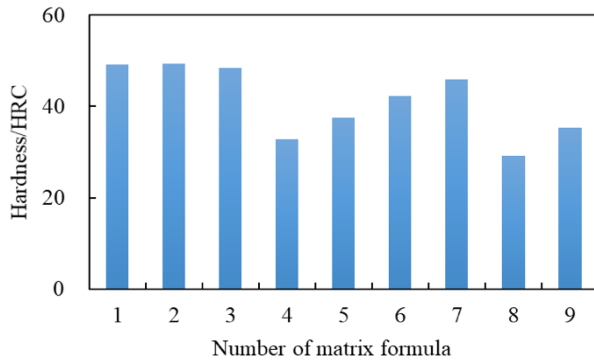


Fig. 8. Check whether this need not be presented in bold font. Apply possible corrections to similar instances in the study.

Fig. 9 shows the bending strength of nine matrixes without diamond and DICs with diamond. Fig. 10 shows the decline rate of the bending strength of the matrix of nine material formulas by calculated the data in Fig. 9. The decline rate of the bending strength of the matrix of No. 3 material (60%WC+15%FeCuXP+25%CuSn) is the minimum at only 14%.

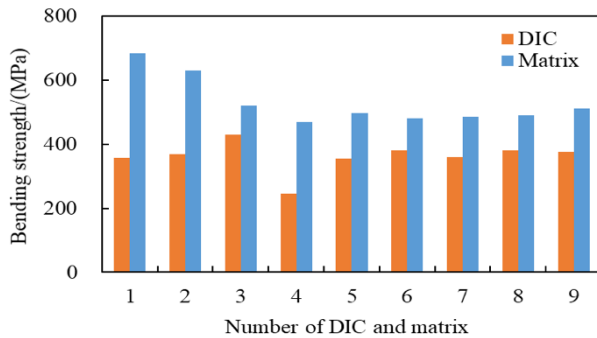


Fig. 9. Bending strength of nine matrixes without diamond and DICs with diamond

According to Figs. 8, 9 and 10, No. 3 material (60%WC+15%FeCuXP+25%CuSn) formula is suitable for sintering DICs.

According to Reference [23], the strength of diamond particles is influenced by both temperature and holding time (Fig. 11). Tables 4 and 6 and Figs. 8, 9 and 10 show that the holding time of hot-pressing sintering is approximately 5 minutes to ensure that diamond particles have sufficient strength. Hence, the performance of the DIC meets the ideal requirements.

4.3 Test analysis of performance of diamond-impregnated cutters with different diamond grain sizes

According to the analyses in Sections 4.1 and 4.2, the hot-pressing sintering method is selected and the sintering temperature is controlled within 980 °C when comprehensive indexes, such as hardness, strength, strength decline rate, and diamond particle strength, are considered.

Diamond particles are added to No. 3 material (60%WC+15%FeCuXP+25%CuSn), and the DIC is sintered. The performance of the DIC with different diamond grain sizes is tested, and the rock breaking performance is analyzed.

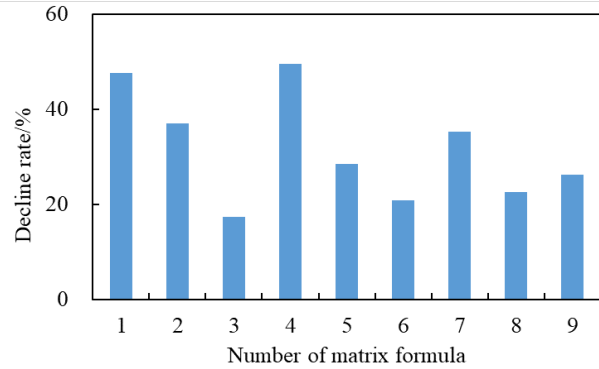


Fig. 10. Column diagram of the decline rate of the bending strength of the matrixes.

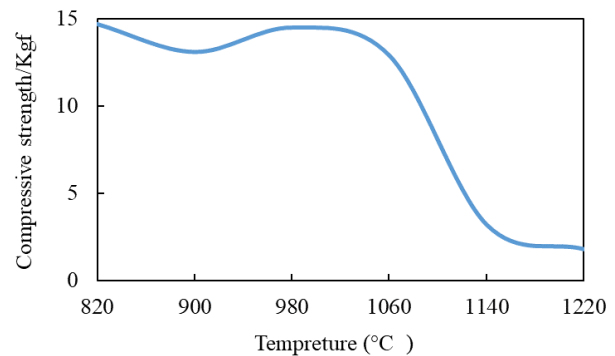


Fig. 11(a). Relationship between the diamond particle strength and the temperature

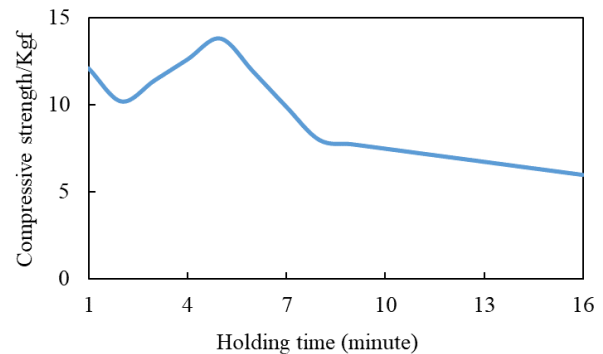


Fig. 11(b). Relationship curve between the diamond particle strength and the heat preservation time

Table 7 shows the relationship between DIC with different diamond parameters and the drilling depth, penetration rate, wear loss, and wear rate.

Table 7. Experimental data at different diamond parameters

	Serial number	Wear loss (g)	Drilling depth (mm)	Drilling time (s)	ROP (m/h)	Wear rate (mg/s)
Single grain size	1	0.1504	40.7	72	2.04	2.09
	2	0.0835	37.67	104	1.30	0.80
	3	0.0325	36.69	152	0.87	0.21
	4	0.0162	42.95	303	0.47	0.05
Composite grain size	1	0.1303	48.96	102	1.73	1.28
	2	0.1094	59.22	138	1.21	0.79
	3	0.0677	44.1	142	1.12	0.48
	4	0.0589	56.1	185	1.09	0.32

Fig. 12 shows the relationship between the diamond grain size and ROP of the DIC. ROP of the DIC reduces with the decrease of the diamond grain size when diamond particles are single grain size. This finding indicated that diamond particles on the working face of the DIC and contact area with rock increase while the pressure on each diamond particle, load of the drilled rock, depth of the diamond particles drilling into the rock, and ROP of the DIC decrease. ROP of the DIC slightly reduces with the decrease of the diamond grain size when the diamond parameter is composite grain size. This finding indicated that the rock breaking efficiency of DIC with the composite diamond grain size is higher than that of the single grain size of DIC.

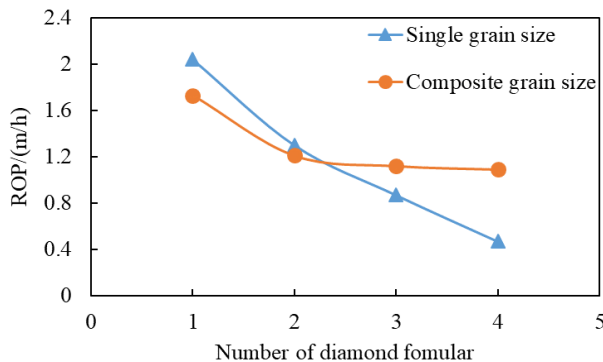


Fig. 12. Relationship curve between diamond grain size and ROP of diamond-impregnated cutter

Table 7 and Fig. 13 show that the wear rate of DIC with single grain size is larger than that with composite grain size when the diamond grain size is large. The wear rate of DIC with single grain size is smaller than that with composite grain size and the wear rate curves of the two kinds of DIC demonstrate intersection points, that is, wear rates are the same as the grain size decreases. The wear rate is an important analysis index of the wear resistance.

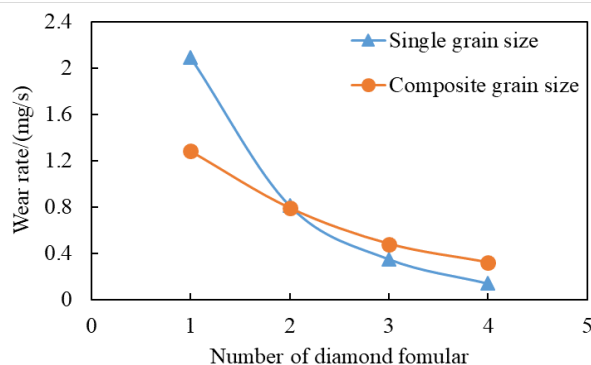


Fig. 13. Influence of the diamond grain size on the wear rate of the diamond-impregnated cutter

The rock-breaking performance of DIC can be evaluated using different parameters in addition to the ROP and wear rate. Figs. 12 and 13 illustrate that although the DIC with high ROP and low wear rate is the most suitable, it does not exist. Therefore, ROP and wear rate should be comprehensively analyzed when selecting diamond parameters. A large ROP indicates a small the wear rate, large comprehensive performance index, and enhanced rock-breaking performance of DIC. Comprehensive performance indexes of DIC are calculated according to the data in Table 7 and Equation (4) and the histogram is shown in Fig. 14.

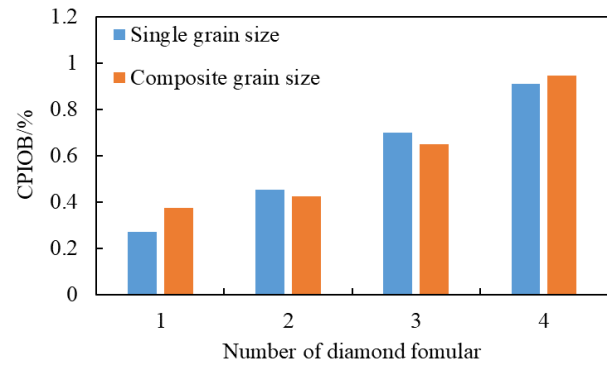


Fig. 14. Comprehensive performance of the diamond-impregnated cutter with different diamond parameters

According to Fig. 14, the comprehensive performance indexes of No. 4 DIC with single grain size and No. 4 DIC with composite grain size are the highest at 0.91 and 0.96, respectively. The comparison of comprehensive performance indexes of DICs with single and composite grain sizes demonstrated that No. 4 DIC with composite grain size exhibits the highest comprehensive performance index.

5. Conclusions

A new method for screening and designing the DIC material formula was proposed in this study with experimental analysis and comparison to develop DIC with high rock-breaking efficiency and long service life suitable for hard stratum. Experimental models of the diamond matrix material, DIC material, and sintering method were established and experimental data of the matrix material were examined by analyzing the requirements of the performance of DIC in hard stratum. Moreover, the DIC material and sintering method suitable for hard stratum were determined. The following conclusions could be drawn:

(1) The DIC calcined via hot-pressing sintering method demonstrates satisfactory wear resistance, high rock breaking efficiency, and long service life with 60%WC+15%FeCuXP+25%CuSn as the basic material and the addition of diamond particles.

(2) ROP of both DICs with single and composite grain sizes is positively correlated with the diamond grain size. A small grain size indicates a small ROP.

(3) The wear resistance of both DICs with single and composite grain sizes is negatively correlated with the diamond grain size. Meanwhile, the wear rate of DIC is positively correlated with the diamond grain size. A small diamond grain size indicates a small wear rate and long service life.

(4) The comprehensive performance index of DIC with single grain size is lower than that with composite grain size. The comprehensive performance index of DIC with single grain size is only 0.91, while that of DIC with composite grain size can reach 0.96.

DIC with high rock breaking efficiency, strong wear resistance, and high comprehensive performance index is designed in this study according to the basic theory of strength, hardness, density, and comprehensive performance index of DIC through the experimental method. Based on experimental data, 60%WC+15%FeCuXP+25%CuSn was selected as the basic material and diamond particles were

added to sinter the DIC. The comprehensive performance comparison of results demonstrated that the DIC calcined with the addition of 60%WC+15%FeCuXP+25%CuSn as the basic material shows acceptable comprehensive performance. The results of the proposed sintering and material screening methods can provide a theoretical reference for developing cutters with satisfactory wear resistance and high rock breaking efficiency, which are commonly used in developing high-quality cutters.

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