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A new composite impregnated diamond bit for extra-hard, compact, and nonabrasive rock formation

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ABSTRACT

In this study, a new composite impregnated diamond bit was designed to solve the slipping problem when impregnated diamond bit is used for extra-hard, compact, and nonabrasive rock formation. The new bit is composed of sintered diamond-impregnated (SDI) cutters and support body. The support body has weaker resistance to abrasion and would thus wear out faster than SDI cutters during drilling operation. Such design decreases the contact area between the bit work layer and the rock formation and increases the unit load acting on the work layer and the single diamond, thereby improving drilling efficiency. The design parameters and manufacturing technology of the new composite impregnated diamond bit were analyzed to achieve the desired performance. Two Φ41/27 mm laboratorial bits were manufactured to conduct a laboratory drilling test on the rock specimens of fine-grained monzonitic granite rich in biotite. The laboratory drilling test indicated that both the manufacturing technology and the drilling parameters significantly affect the rate of penetration (ROP). The test also indicated that the abrasive resistance of the bit work layer was proportional to the area ratio of SDI cutters to bit bottom face. A very small or very large area ratio in the radial direction causes annular groove or wale at that section, respectively. Therefore, optimization was conducted to coordinate the abrasiveness of the drilled rock formation and abrasive resistance of the bit work layer, and a Φ91.5/71 mm composite impregnated diamond bit was manufactured. The new bit was applied to a hydropower station drilling construction in Fujian Province, China. Field drilling application indicated that the ROP of the new bit was approximately three to four times that of the bits produced by other factories. The ROP relationship was completely similar to the ratio of the applied load acting on a single diamond of the new composite to ordinary impregnated diamond bits.

1. Introduction

Drilling is the most important operation for mining and prospecting industries. The probability of encountering slipping formation during drilling operations has increased because of the development of energy explorations in deep rock formations. In the drilling community, slipping formation is the informal name for extra-hard, compact, and nonabrasive rock formation. This formation usually has three characteristics [1]. (1) Rock hardness is relatively high because of the high quartz content. The rock hardness of slipping formations is approximately 5000 MPa but reaches up to 7000 MPa for a number of special formations. (2) Rock strength is high because the rock-forming mineral grains are very small (with diameters ranging from 0.01 mm to 0.2 mm) and have local siliceous cementation. Thus, an overall uniaxial compressive strength of 150 MPa or higher can be achieved because of the compact structure. (3) Rock abrasiveness is weak. The low rate of penetration (ROP) results in small rock debris. Therefore, the debris abrasiveness to the bit matrix is limited, and diamonds do not easily emerge from the bit matrix.

An essential feature of slipping drilling is that the diamond protrusion height on the bit bottom face is too short or almost nonexistent. The bit bottom face appears somewhat like a mirror finish. Several methods have been employed in field drilling applications to address this issue [2]. These methods include grinding the bit matrix under dry condition drilling, putting quartz sand at the bottom of the well, hammering the bit bottom face, and using acid to treat the bit bottom face. However, these methods can only be used in shallow wells; otherwise, the drilling efficiency would be affected, the probability of drilling accidents would increase, and a number of unnecessary difficulties and losses may occur.

Numerous studies were conducted to address the difficulties in hard rock drilling. For instance, various indices, such as total silica content, grain shape factor, shore hardness, and abrasiveness, were found to be responsible for the bits' wear rate in rock drilling [3]. The performance of polycrystalline diamond compact cutters under different combined loads of static thrust, impact, cutting, and water jets on Missouri red granite and Halston limestone were investigated to verify the feasibility

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and efficiency of rotary–percussive drilling assisted by water jets for very hard rocks [4]. Laboratory tests were conducted on rocks (such as sandstone, limestone, granite, and basalt) to investigate the applicability of ultrasonic percussive drilling with diamond-coated tools to downhole drilling [5]. Nonionic polymer was added to the flushing media to enhance the diamond drilling performance on phosphate rock [6]. Particle impact drilling was experimentally studied for deep well hard formation [7]. Gao [8] designed a bionic coupling impregnated diamond bit specifically for hard rock formation drilling. However, the slipping formation differs from these ordinary hard rock formations in terms of nonabrasive property.

This study presents a new diamond bit structure to solve the drilling difficulties in extra-hard, compact, and nonabrasive rock formation. This design steadily maintains a small contact area between the diamond bit work face and the rock formation during drilling to increase the unit load acting on the single diamond and improve the ROP.

2. Design of the new diamond bit

2.1. Methodology

Several commonly accepted principles in the drilling industry are related to the manufacture of impregnated diamond bits for slipping formations. For example, a diamond bit with heterogeneous bottom face can be employed to decrease the contact area between the bit work face and the rock formation, thereby increasing the free surfaces when breaking rocks [9]. Choosing a matrix with low abrasive resistance can impel the diamond protrusion, and decreasing the diamond concentration can improve the load acting on each single diamond [10].

In terms of diamond parameters, high quality and strength are usually required; however, the required particle size remains debatable. Ye [11] used theoretical calculation to show that a macrograined diamond improves the average load acting on the single diamond of the bit bottom face; such improvement benefits the diamond protrusion.

Moreover, several methods, such as hot-pressed or electroplated bits with weak diamond retention [12,13] and hot-pressed diamond bits with principal and secondary abrasives [14], have been employed to ensure that weaker abrasives participate in wearing out the bit matrix.

After a comprehensive review of previous studies, we found that three aspects were important for bit structural design. (1) Diamonds with high quality, high strength, and large particle size were required to resist the high bit load. (2) The capacity of the bit matrix resistance to abrasion should be weaker because the rock debris is very small. Thus, the debris abrasiveness to the bit matrix should be enhanced. (3) The contact area between the bit work face and the rock formation should be as small as possible to increase the unit load acting on the bit work face.

We designed a new composite impregnated diamond bit with weaker matrix resistance to abrasion and sintered diamond-impregnated (SDI) cutters to achieve the desired design objectives. The configuration of the new composite bit work face is shown in Fig. 1.

As shown in Fig. 1, two sets of drills, namely, one with (a) arrangement and one with (b) arrangement, were used. The SDI cutter was manufactured through hot pressing, and it could be either cuboid or cylindrical. The support body was the bit matrix with lower hardness and weaker abrasiveness, and was designed to embed SDI cutters and maintain a connection between the bit blank body and the bit work layer.

2.2. Diamond parameters and matrix formula

Previous studies [15] indicated that diamonds normally present six different states during cutting operation: emerging grit, integral grit, smoothed grit, micro-fractured grit, macro-fractured grit, and pull-out. These states are usually closely related to the properties of diamond grits. Higher diamond compression strength and impact toughness correspond to less diamond breakage during operation, resulting in tool property improvement [16]. In this study, we selected the ZND2160 diamond type (Zhongnan Diamond Co., Ltd., China) for the SDI cutters because of its high quality (diamond concentration: 25 vol.%). Mixed mesh consisting of 40/45 US mesh (17.5 vol.%) and 50/60 US mesh (7.5 vol.%) was used in this study. The mechanical parameters of two US mesh size diamonds are shown in Table 1.

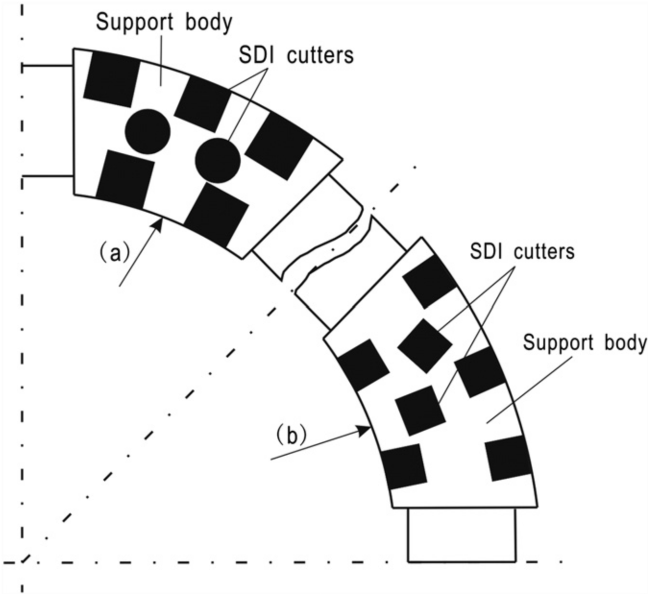

Fig. 1. Configuration of the new composite impregnated diamond bit to illustrate the cutting structure for slipping formation.

The bit matrix is the component that embeds the diamond grits and connects the bit's blank body. The adaptability between the bit matrix and the drilled rock formation properties plays an important role in bit quality. In other words, difficulties in slipping drilling indicate that the properties of bit and rock formation are not adaptable. Thus, the matrix formula for the SDI cutters and the support body should be separately designed.

The metallic matrices of tungsten carbide, cobalt, and iron are the most frequently used matrices for impregnated diamond bits. In contrast to other matrices, the tungsten carbide-based matrix has high sintering temperature, excellent hardness, and strong abrasive resistance. Cobalt is widely regarded as the best metal material for metallic matrices [17]. Cobalt-based matrix has good toughness, moderate hardness, and average abrasive resistance. Similar to cobalt, iron is an eighth group element; thus, these elements have similar properties. Iron-based matrix has relatively weak hardness and abrasive resistance but is recently widely used because of its low cost and availability [18,19]. The hardness and abrasive resistance of the support body should be weaker so that the support body can be worn out more easily than the matrix of SDI cutters and the bit load can be focused on the SDI cutters. Thus, an iron-based matrix was preferred.

SDI cutters are the cutting parts during the drilling process. The matrix of the cutters should be sufficiently hard and strong to resist the high bit load on the cutters' bottom faces and to embed the diamond grits strongly. Therefore, a tungsten carbide-based matrix would be preferable. The matrix formulae for the SDI cutters and the support body are shown in Table 2.

Table 1
Diamond grit parameters and concentration.

Diamond type	Grit size (US mesh)	Toughness index (%)	Thermal toughness index (%)	Concentration (vol.%)
ZND2160	35/40	88 to 91	83 to 87	17.5
ZND2160	50/60	80 to 83	77 to 78	7.5