Influence mechanism of hard brittle grits on the drilling performance of diamond bit

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ABSTRACT. This paper attempts to improve the drilling efficiency of diamond bit in hard and complex formation by adding a proper concentration of hard brittle grits into the matrix. For this purpose, the most suitable material for hard brittle grits was selected, the effects of hard brittle grits on matrix wear features were studied through drilling experiments and scanning electron microscope (SEM) examination, and the impact of grit distributions on the cutting performance of single diamond was discussed in great details. The experimental and analysis results show that 300μm SiC is the most suitable material for hard brittle grits; the most efficient diamond bit should have a diamond size of 45/50 US mesh, diamond concentration of 67%, hard brittle grit concentration of 37% and matrix hardness of 15 (Rockwell hardness, HRC). It is also found that the distribution pattern of hard brittle grits in the matrix directly bears on the cutting performance and failure mode of single diamond, and the impact of hard brittle grits on drilling performance is the combined effect of the grits obeying different distributions. The research findings shed new light on the improvement of diamond bit in actual engineering.

RÉSUMÉ. Cet article tente d'améliorer l'efficacité de forage du foret de diamant dans les formations dures et complexes en ajoutant une concentration appropriée de grains durs et fragiles dans la matrice. A cet effet, le matériau le plus adapté à grains durs et fragiles a été sélectionné, les effets des grains durs et fragiles sur les caractéristiques d'usure de la matrice ont été étudiés par des expériences de forage et d'un examen au microscope électronique à balayage (SEM), et l'impact des distributions de grains sur la performance de coupe de seul diamant a été discuté en détails. Les résultats expérimentaux et d'analyse montrent que 300 μm de SiC est le matériau le plus approprié pour les grains durs et fragiles; le foret de diamant le plus efficace doit avoir une taille de diamant de 45/50 mesh US, la concentration en diamant de 67%, la concentration en grain dur et fragile de 37% et une dureté de matrice *de 15 (dureté Rockwell HRC). On constate également que le modèle de distribution des grains durs et fragiles de la matrice a une incidence directe sur les performances de coupe et le mode de défaillance du diamant unique, et l'impact des grains durs et fragiles sur les performances de forage correspond à l'effet combiné des grains suivant différentes distributions. Les résultats de la recherche apportent un nouvel éclairage sur l'amélioration de foret de diamant dans l'ingénierie réelle.*

KEYWORDS: diamond bit, hard brittle grits, hard rock drilling, wear morphologies.

MOTS-CLÉS: foret diamant, grains durs et fragiles, forages de roches dures, morphologies d'usure.

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1. Introduction

Impregnated diamond bit is a popular drilling tool for oil production, geological exploration, and civil construction (Xu *et al*., 2016; Patrik *et al*., 2016). With the development of deep scientific drilling and unconventional energy exploration, the probability for the drilling bit to encounter hard and complex formation has increased (Sun *et al*., 2016). This kind of formation features high rock strength, high rock hardness, and weak rock abrasiveness (Chen and Liu, 2006). The rock strength arises from local siliceous cementation and small mineral grits, the rock hardness originates from the high quartz content, and the rock abrasiveness is resulted from the low rate of penetration (ROP). Owing to the limited abrasiveness of rock debris against the bit matrix, it is difficult for the diamond to emerge from the matrix, thus reducing the drilling efficiency.

During the drilling process, the bit performance hinges on the synchronous wear between diamond and matrix. Therefore, much research has been done to improve synchronous wear performance, aiming to overcome the drilling difficulties in hard and complex formation. For instance, Tan *et al*. (2014) explored the wear mechanism of composite impregnated diamond bit and examined the process of rock fragmentation. Wang *et al*. (2016) studied the wear behaviour of bionic impregnated diamond bit, revealing the relationship between bionic unit parameter and microscopic wear morphology of matrix. Based on thermodynamics and chemical kinetics theory, Pang and Duan *et al*. (2015, 2014) disclosed how physical-chemical behaviours of the pore affect the microscopic wear morphology of the matrix. Gui *et al*. (2011) conducted experiments on particle impact drilling in deep well and hard formation.

Recent years has seen the rise of a new method to improve the synchronous wear performance between diamond and matrix: adding a proper concentration of hard brittle grits, e.g. SiC and Al_2O_3, into the matrix. These grits, commonly used in grinding process, can true and dress diamond grinding wheel and fixed abrasive pad (FAP) in the form of abrasive stick, free abrasives and grinding wheel. Kim *et al*. (2013) investigated the effect of free Al_2O_3 grits on self-sharpening performance of the FAP, pointing out that the working efficiency of resin-based FAP can be enhanced by a proper concentration of free Al_2O_3 grits. Zhu *et al*. (2015) probed into the influence mechanism of free SiC grits on self-sharpening performance of resin-based FAP. Sun *et al*. (2016) explored the impact of SiC size on self-sharpening performance of ceramic matrix diamond abrasive disk. Shen *et al*. (2017) discussed the effect of hard brittle grits on diamond bit drilling efficiency in hard and compact formation. Our previous research indicates that adding a proper concentration of hard brittle grits into matrix helps to lower the wear resistance of the matrix and bolster drilling efficiency (Wang and Zhang, 2016; Wang and Zhang, 2015). To sum up, the existing research into the effect of hard brittle grits on drilling performance has concentrated on engineering practice rather than theoretical analysis.

Considering the above, this paper attempts to further study the influence of hard brittle grits, especially their distribution pattern, on the drilling performance of diamond bit.

2. Experimental study

2.1. Hard brittle grit type

The hard brittle grits in our experiments include Al_2O_3, SiC and alloy steel shot. The physical-mechanical parameters of these materials are presented in Table 1. With a trigonal system, the hard and tough Al_2O_3 grits (Mohs hardness: 9) are suitable for grinding materials of high tensile strength. The size of Al_2O_3 grits in our experiments averages at 425μm. With a hexagonal system, SiC has a higher Mohs hardness (9.5) than Al_2O_3, and a lower toughness than the latter. The average size of SiC in our experiments stands at 300μm. The alloy steel shot boasts the highest hardness (Rockwell hardness (HRC): 55) among the three materials. Thanks to its low porosity, homogeneous density and excellent abrasion resistance, the alloy steel shot has been extensively applied to polish and sandblast stainless steel and aluminium castings. In our experiment, the average size of steel shot is 380μm.

Table 1. Composition of matrix material %

Type	Chemical component (%)								Grain size (μm)
	Al2O3	SiC	Mn	Fe2O3	C	CaO	SiO2	Si	
Al2O3	>95%	-	-	<0.15%	-	<0.4%	<1.5%	-	425μm
SiC	-	>98.5%	-	<0.6%	-	<0.2%	-	-	300μm
Steel shot	-	-	-	0.35-1.2%	-	0.7-1.2%	-	0.4-1.2%	380μm

Four bits with HHD80 diamond (Henan Huanghe Whirlwind Co., Ltd., China) were selected, and tested with different kinds of hard brittle grits in our experiment.

As shown in Table 2, the four bits share the same matrix hardness (HRC: 15) and grit size (45/50 US mesh), but differ in diamond concentration (75%, 69%, 67% and 70%). For comparison, Bit 1 does not contain any hard brittle grit. Bit 2, Bit 3 and Bit 4 were applied with Al_2O_3, SiC and alloy steel shot, respectively. For the latter three bits, the grit concentration was maintained at 30%, 38% and 18%, respectively, and the grit size at 425μm, 300μm, 380μm, respectively. Each bit is 35mm in outer diameter and 21mm in inner diameter, and has four 4mm-wide and 6mm-tall slots.

Table 2. Experiment bits parameters

No	Hardness /HRC	Diamond concentration/Vol	Diamond size /mesh	Hard brittle grits concentration /Vol	Hard brittle grits size/mesh	Hard brittle grits type
1	15	75%	45/50	-	-	-
2	15	69%	45/50	30%	425 μm	Al_2O_3
3	15	67%	45/50	38%	300 μm	Silicon carbide
4	15	70%	45/50	18%	380 μm	Steel shot

2.2. Experimental equipment setup and procedure

The bits were sintered in an Automatic Controlled ZPM Intermediate Frequency Furnace, whose temperature range falls in 600~1,200°C. Several drilling experiments were performed on a test bench with a 2,800W spindle drive motor at the available speeds of 700, 750, 850 and 980 RPM, respectively. During the experiments, water coolants are applied to maintain the surface temperature of the bits. The water pressure and flow rate were set to 0.4MPa and 15L·min-1, respectively. The microscopic abrasive morphology and features of the bits were observed by a 6700F scanning electron microscope (SEM) equipped with energy dispersive spectrometry (EDS).

Table 3. Composition of ZAS (%)

ZrO_2	Na_2O	SiO_2	Fe_2O_3	Al_2O_3
36	14	14	0.30	Margin

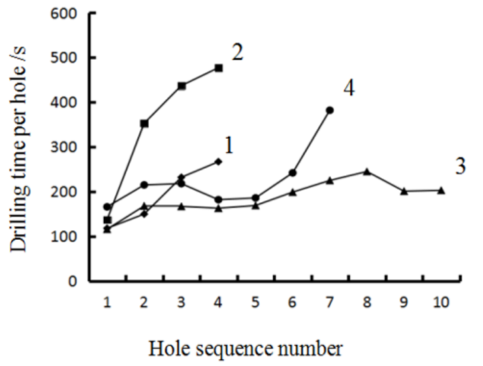
The test specimens are zirconia corundum refractory brick (AZS), whose compositions are given in Table 3. In 1984, the Ministry of Geology and Mineral Resources of China issued a rock drillability grading standard for diamond drilling, which divides the rock drillability into 12 grades. According to this standard, the specimens are hard rocks of the tenth grade, i.e. the rock is very hard to drill.

In addition, the tool life was represented by the total drilling distance, while the drilling efficiency was characterized by the mean drilling time of each hole.

3. Result and discussion

3.1. Drilling performance

Figures 1 and 2 respectively illustrate the drilling efficiency and tool life of the four bits under the axial force of 2.5~3.5MPa and spindle speed of 750RPM. During the experiments, the drill bit was pulled out at the drilling footage of 80mm to start a new drill hole.



1- bit #1； 2- bit #2； 3- bit #3； 4- bit #4

Figure 1. Drilling efficiency of the bits

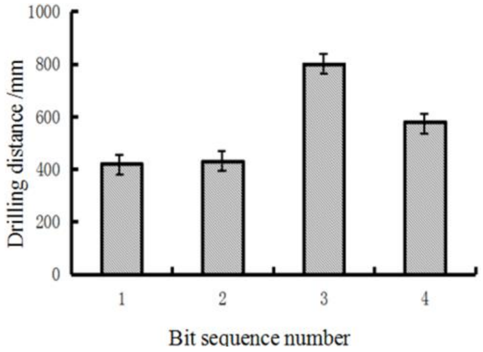


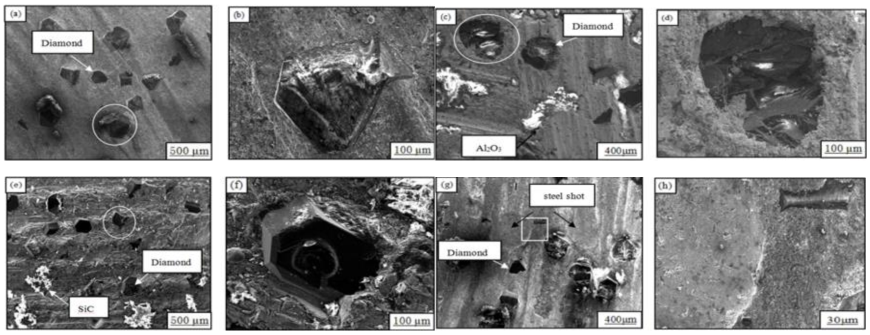
Figure 2. Drilling distance of the bits

It can be seen that Bit 2 with Al_2O_3 had the longest mean drilling time, that is, the lowest drilling efficiency. The drilling efficiency declined after drilling 2 holes (drilling distance: 160mm) under the axial force of 2.5MPa. When the axial force grew to 3.0MPa, the bit suffered from greater radial vibration and the machine spindle stalled due to the lack of power. The drilling process was halted after drilling 5 holes (drilling distance: 400mm).

Compared to Bit 2, Bit 1 had a similar drilling distance (400mm) and a relatively high drilling efficiency. The drilling efficiency decreased after drilling 3 holes (drilling distance: 240mm) under the axial force of 2.5MPa. When the axial force rose to 3.0MPa, the drilling efficiency increased slightly and a continuous high-pitched noise was noted during the drilling process. Bit 1 could no longer drill normally after drilling 5 holes (drilling distance: 400mm).

Bit 3 with SiC enjoyed the best drilling efficiency. It drilled over 10 holes (drilling distance: 800mm) effectively without no slipping. The drilling efficiency of Bit 4 with alloy steel shot was higher than that of Bit 1 and Bit 2, but lower than that of Bit 3. The drilling efficiency declined after drilling 3 holes (drilling distance: 240mm), turned up slightly when the axial force increased to 3.0MPa, and fell again after drilling 6 holes (drilling distance: 480mm). Bit 4 could no longer drill normally after drilling 7 holes (drilling distance: 560mm) under the axial force of 3.5MPa. Overall, Bit 3 with SiC presented the best drilling performance in this experiment.

3.2. Abrasion appearance



Figue 3. SEM micrographs of wear morphology on the reference sample: (a) the worn surface of bit#1; (b) the amplified picture of the circled area in Figure (a); (c) the worn surface of the bit #2; (d) the diamond amplified picture of the circled area in Figure (c); (e) the worn surface of bit #3; (f) the diamond amplified picture of the circled area in Figure (e); (g) the worn surface of the bit #4; (h) the amplified picture of the square area in Figure (g)

Figure 3 shows typical wear morphology on matrix of the four bits. Figure 3(a) presents the wear morphologies of the bit #1. Figure 3(b) is the amplified picture of the circled area in Figure 3(a). As seen in Figure 3(a), the matrix at the frontal and lateral sides of the diamond presents shallow worn grooves and behind the diamond bond tails are also formed owing to the less erosion of the matrix. In Figure 3(a), it also can be found that diamond protrusive heights for most grains are low and less amount of pull-out diamonds is found. In addition, many flatten or smoothed diamonds are observed. Figure 3(b) shows one of the diamond with smooth surface. The matrix surface has no distinctive characteristics of abrasive wear due to the few and weak-abrasion of debris in the drilling process, causing a low wear rate of the matrix and a low rate of diamond exposure.

It can be seen from Figure 3(c) that Al_2O_3 grits obeyed flat distribution in the matrix; there was no distinctive features of brittle crush or abrasive wear on the matrix surface; the flattening and smoothing of diamond were more severely than those of Bit 1. The severe diamond flattening and smoothing can be explained in dimensions. First, Al_2O_3 with a low brittle fracture ratio, cannot be exfoliated easily from the matrix, which constrains the abrasive ability of the grits and the protrusion height of the diamond; in the macro scale, the drilling process becomes less efficient. Second, Al_2O_3 occupies a large volume in the bit, leading to a dramatic decrease in the volumetric concentration of diamond and the number of exposed diamond grits per unit area; the resulting increase in the load on each diamond induces even more wears under high bit pressure. Figure 3(c) also demonstrates the horizontal and vertical scratches on the matrix surface, and the absence of bond tails behind the diamond. These phenomena can be explained as follows. Bit 2 vibrates laterally during slipping in the early phase of drilling; the vibration increases sharply under the high pressure in later phases, leading to serious damages on diamond bond tails and horizontal/vertical scratches on the matrix surface.

According to Figure 3(e), the matrix surface of Bit 3 carried typical features of abrasive wear, and diamond bond tails were formed; there were drift sands surrounding diamond grits, and different crush morphologies of the diamond were observed and maintained at a certain proportion. This means the metabolic rate of the diamond matches the wear rate of the matrix. The grooves on the front and lateral sides of the diamond grits were deeper than Bit 1, which retains large rock debris at hole bottom and enhances the grinding ability of the debris (Zhao and Zhang, 2011; Gao and Yuan, 2011). From Figure 3(f), it is clear that SiC grits in the matrix were irregular and brittle; the protrusion height of diamond was relatively high; however, abnormal crush was found on diamond surface due to the low quality of the diamond. Hence, high grade diamond should be adopted for drilling bit. In general, the influence of SiC grits is two-fold. For one thing, a proper concentration of SiC grits in the matrix can reduce the diamond volume per unit area, and increase the beta ratio of bit bottom face due to their brittle fracture features and irregular shape; for another, the grits can strengthen the abrasive ability of debris and promote diamond protrusion (Wang and Zhang, 2015; Guo *et al*., 2015; Wang *et al*., 2016).

Figure 3(g) shows that Bit 4 share similar wear morphologies with Bit 1: shallow worn grooves were observed on the matrix at the front and lateral sides of the diamond, and bond tails were also formed behind the diamond. In the figure, the arrows stand for the alloy steel elements tested by energy spectrum analysis. It can be found that the alloy steel shots were shaped regularly, with no distinctive fracture with the matrix. This means the matrix and alloy steel shots have an excellent bonding strength. In addition, steel shots can form shallow concave pits in the matrix during drilling, and exhibit no brittle fracture features. A proper ratio of these pits in the matrix helps to collect residual rock debris, enhance the load on each diamond, and improve diamond exposure. It is also learned that Bit 4 exceeded Bits 1 and 2 in terms of drilling distance. The reason is that alloy steel shots are denser and more regular than Al_2O_3 grits; under the same mass, alloy steel shots occupy a smaller volume in the matrix than Al_2O_3 grits, resulting in a proper reduction in the diamond volume per unit area. Unlike SiC grits, alloy steel shots exhibited no brittle fracture features. Since brittleness is a promoter of debris abrasive ability, alloy steel shots cannot boost diamond protrusion as good as SiC grits. That is why slipping occurred in the later phase of the drilling process. In summary, Bit 3 with SiC is the best choice for actual drilling.

3.3. The influence of the distribution pattern of hard brittle grits on the cutting performance of single diamond

The experimental results indicate that the random distribution of hard brittle grits in the matrix can improve the drilling performance of diamond bit in two ways: improving the microscopic wear morphology of matrix and enhancing the cutting performance of single diamond. The influence mechanism of hard brittle grits on the cutting performance and failure mode of single diamond may vary with the grit positions. The relative positions between the grits and diamond in the matrix are illustrated in Figure 4.

If the hard brittle grits and diamond are not connected together in the matrix such as Figure 4(a), the hard brittle grits mainly cause the micro-pits effect in the matrix by micro brittle fracture character, which can improve microscopic wear morphology and promote diamond exposure indirectly. Nevertheless, the micro brittle fracture has less impact on microscopic wear morphology of the matrix than bulk fracture. Thus, the distribution pattern in Figure 4(a) has a limited enhancement effect on drilling performance.

With the concentration of hard brittle grits increased, certain proportion of hard brittle grits and diamond contact with each other in the matrix. Along the cutting direction, if the hard brittle grits in front of and contact with the diamond such as Figure 4(b) and Figure 5(a), the hard brittle grits can increase the protrusion height of single diamond, because of the brittle fracture and lamellar exfoliation of hard brittle grits in the drilling process. Moreover, free hard brittle grits which enriched in front of the single diamond in the down hole can produce truing and sharpening effect on the single diamond directly, therefore improve the cutting performance of single diamond and the drilling efficiency. Hence, the distribution pattern shown in Figure 4(b) has large effect in improving drilling performance.

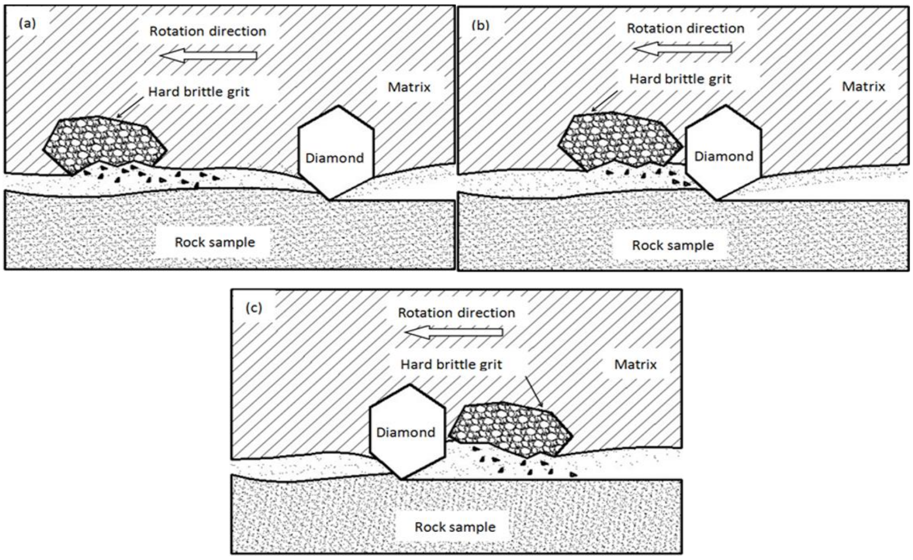


Figure 4. Schematic representation of the locations of hard brittle grits and diamond:(a) no contact between hard brittle grit; (b) hard brittle grit locates in front of and contact with diamond; (c) hard brittle grit locates behind and contact with diamond

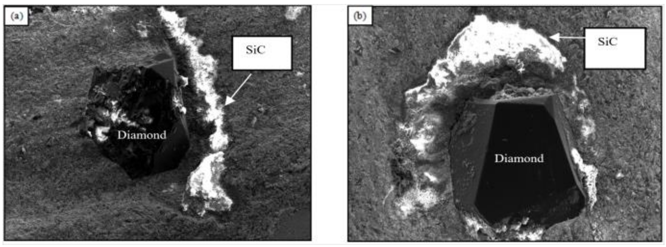


Figure 5. Schematic representation of the locations of hard brittle grits and diamond when they are in contact: (a) hard brittle grit locates in front of diamond along the cutting direction; (b) hard brittle grit locates behind of diamond along the cutting direction

Along the cutting direction, if the hard brittle grits locate behind of and contact with the diamond such as Figure 4(c) and Figure 5(b). On one hand, the micro-fracturing and fall off the hard brittle grits can increase the protrusion height of the diamond in front. On the other hand, the back supporting force to the diamond will be reduced, and may cause the diamond fall off ahead of time. The remaining free diamond particles, hard brittle grit particles and the cuttings can all cause abrasiveness to the matrix and facilitate the protrusion of diamond. Therefore, the distribution pattern shown in Figure 4(c) has the greatest effect on improving drilling performance. However, if too many diamonds falled off ahead of time, the drill bit life will be reduced.

In conclusion, the effect of hard brittle grits to the drilling performance is a combination of the effect of hard brittle grits with different distribution patterns.

4. Conclusions

This research shows that drilling efficiency depends on both the type and distribution of hard brittle grits in the matrix. Through the experiments and result analysis, the author drew the following main conclusions.

First, 300μm SiC is the most suitable material for hard brittle grits. The effect of hard brittle grits on the drilling performance of diamond bit comes from the improved microscopic wear morphology of the matrix and the enhanced cutting performance of single diamond. The grits can change the micro-morphology of the matrix with their brittle fracture features, laying the basis for the normal protrusion of diamonds. Besides, the exfoliation of free grits can increase the solid content in the drilling fluids, which also facilitates the protrusion.

Second, the most efficient diamond bit should have a diamond size of 45/50 US mesh, diamond concentration of 67%, hard brittle grit concentration of 37% and matrix hardness of HRC15.

Third, the distribution pattern of hard brittle grits in the matrix directly bears on the cutting performance and failure mode of single diamond. The impact of hard brittle grits on drilling performance is the combined effect of the grits obeying different distributions. For better drilling efficiency and longer bit life, the future research will focus on the optimization of distribution patterns of hard brittle grits in the matrix.

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