[Article ID] 1003- 6326(2002)02- 0305- 05

Cutting capacity of PDC cutters in very hard rock①

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[Abstract] An experimental programm of investigating the cutting capacity of PDC flat cutters in very hard rock has been performed. Experiments include both the cutting of PDC fixed at different angles on the granite core or bar and linear cutting with different static thrust on the block of granite. The effects of the rough degree of rock surface, cutting angles, and static thrust on the cutting capacity of PDC in very hard rock were investigated and analyzed. The results show that the single mode of rotary drilling using PDC cutters is not applied for very hard rocks.

[Key words] cutting test of rock; PDC cutters; rotary drilling
[CLC number] P634.5 **[Document code]** A

1 INTRODUCTION

Since the introduction of Polycrystalline diamond compact (PDC) bits in the mid-1970's, these tools have made tremendous improvements in drilling rate, efficiency, cost and the range of use[1~5]. Now PDC bits can successfully be used in drilling formations ranging from soft to medium hard. By today's standards hard formations for PDC bits typically hover about 120 ~ 150 MPa, unconfined compressive strength range[6,7]. Until now, no any successful case has been reported in drilling extremely strong and abrasive formations such as granite, volcanics or old dolomite.

Usually, researchers attribute the reasons which limit PDC use in harder formations to the two basic performance limits of PDC cutters: the maximum threshold impact force that can be sustained and a thermal limit that dictates wear rate[8~10]. The limited impact resistance of PDC cutters often results in PDC damage under repeated loading in hard formations. Also, hard, abrasive formations can generate high levels of friction at the cutter/rock interface which heats the bit and accelerates the damage to the PDC[9]. Hence these years, one tries to improve the quality of cutters, both in terms of abrasion resistance and impact resistance, so that PDC cutters can drill much harder rocks than they currently do. However, so far, few reports concern the cutting capacity of PDC bits in very hard rocks. In this paper, The effects of the rough degree of rock surface, cutting angles, and static thrust on the cutting capacity of PDC in very hard rock were investigated and analyzed.

2 LABORATORY TEST EQUIPMENT

These tests included both pure cutting of PDC in lathe on granite core and bars, and linear cutting with different static thrusts. The samples tested are Missouri red granite. Its uniaxial compression strength is 240 MPa, and the Schmidt rebound index measured by RM710 is 43.5.

The configuration of the pure cutting tests carried out in a lathe is shown in Fig. 1. The cored rock samples with smooth surface, and the square bar rock samples, were set in a lathe and machined by the PDC cutters fixed at different cutting angles. The square bar samples were used to generate an impact on the PDC cutter so that they were equivalent in

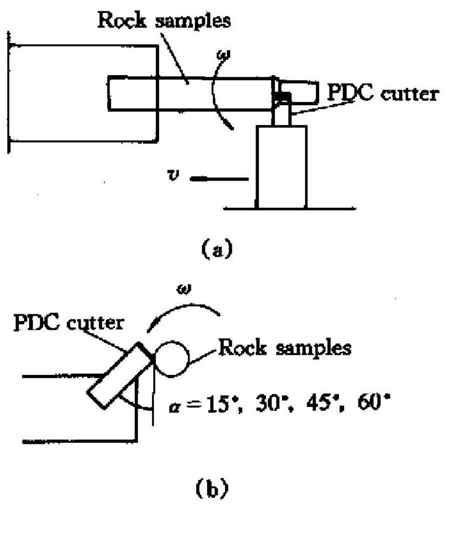

Fig. 1 Cutting of rock samples in lathe

① [Foundation item] Project (50174056) supported by the National Natural Science Foundation of China; project (DE- FG03) supported by the Novatek under the Department of Energy, USA
[Received date] 2001- 03- 13; [Accepted date] 2001- 05- 26

principle to that encountered at the bottom of a hole subject to rotary drilling in very hard rocks. The relative position between the rock samples and the PDC cutter is shown in Fig. 1(b). The cutting angles were designed for 15°, 30°, 45° and 60°.

The linear cutting was conducted on the linear multi-function test table shown in Fig. 2. This table is composed of a moving platform driven by an underlying hydraulic cylinder, which provides the rock with a cutting force F_c. The rock samples are set and fixed on this platform. One thrust cylinder is used to set up a known static thrust force (or weight on bits) into the rock. To provide the rock with an impact force through the PDC, a rod with hammers is put on a movable transmitted rod which is used to transmit the impact to the PDC. The cutting velocity can be controlled by changing the speed of the moving platform. If necessary, a waterjet nozzle can be mounted on the holder of the PDC cutter so that high pressure water jets can be provided for the rock.

3 RESULTS AND DISCUSSION

3.1 Cutting of rock samples in a lathe

Table 1 and Table 2 list the results of cutting the cored granite samples and the square rock bars in a lathe mounted with PDC inserts. The cutting results show that for the cored granite with a smooth surface, no matter what angles the PDC cutters cut, they were not broken, even though the maximum cutting depth reached 3.3 mm (0.13 inch). However, the result of cutting the square basalt bars shows that the PDC cutters were easily damaged, relative to the cored rock with smooth surfaces, when subject to the impact forces generated by their rotation. Meanwhile, the effect of the cutting angles of the PDC cutters on the damage of the PDC was serious. The results show that the lower the cutting angle, the more effective the cutting action of the PDC cutters, with less damage to the PDC, which is consistent with the results of full-scale linear cutting and actual drilling. Severity of damage to the PDC cutter is easily explained by analyzing the force withstood by the PDC. Fig. 3 shows that when the cutting angle $\alpha = 0°$, PDC just withstands a compressive force, while $\alpha = 90°$ PDC turns to pure shearing.

Here, it must be emphasized that the cutting of rock samples in a lathe is different from the full-scale linear cutting or rotary drilling of PDC bits on rocks in the magnitude and type of the force withstood by the PDC cutters. For rotary drilling, or full-scale linear cutting, the cutter withstands both the static thrust and cutting force, while for cutting in a lathe only a cutting force from rotary of the rock samples acts on the cutter. In addition, because of a larger contacting area, or cutting area, between the cutter and the rock, and a complicated confined condition, the cutting force F of the cutter in rotary drilling or full-scale cutting is much larger than that in a lathe, as shown in Fig. 4. However, as a comparison of the influence of different cutting angles on the cutting efficiency and ability of the cutters to withstand loads, it is feasible to machine off the layers of rock using the PDC cutters in a lathe.

3.2 Linear cutting of granite with smooth surface

Cutting test simulating rotary drilling of PDC bits was performed in the linear test table. The tested granite is a cure block with a size of 500 mm. As a comparison, the cutting with the same test condition as the granite was done in the block of concrete without coarse aggregates. In these tests, different static thrusts (WOB) were available by changing hydraulic pressure in the hydraulic cylinder. A single cutter was inclined into the surface of granite or concrete at 45°. The linear cutting velocity was fixed to about 130 mm/min. Table 3 and Fig. 5 shows the linear cutting results for granite and concrete.

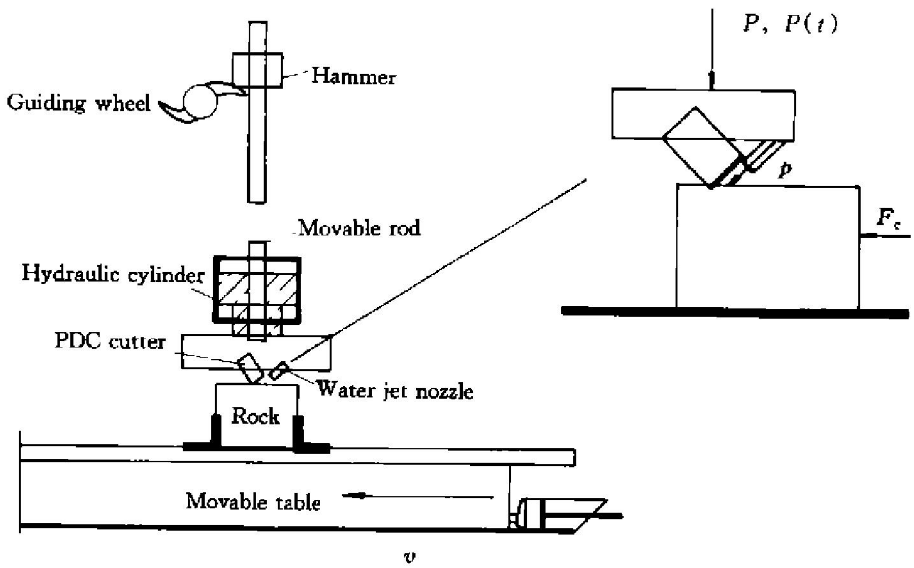

Fig. 2 Principle and layout of linear table

Table 1 Results of cutting of granite cores with smooth surface

PDC angle/(°)	Cutting depth/mm	Spin velocity/(r·min^{-1})	Feed velocity/(mm·r^{-1})	Cutting time	Notes
15	1.27	194	1	1 min	PDC not broken
	1.52	194	1	1 min	PDC not broken
	1.78	194	1	1 min	Rock broken
30	1.52	194	1	53 s	PDC not broken
	1.78	194	1	53 s	PDC not broken
	2.03	194	1	53 s	PDC not broken
	2.29	194	1	53 s	PDC not broken
	2.54	194	1	53 s	PDC not broken
	2.79	194	1	53 s	PDC not broken
	3.05	194	1	53 s	PDC not broken
	3.30	194	1	53 s	PDC not broken
45	1.02	194	1	40 s	PDC not broken
	1.27	194	1	40 s	PDC not broken
	1.52	194	1	40 s	PDC not broken
	1.78	194	1	20 s	Rock broken
	1.78	194	1	40 s	PDC not broken
	2.03	194	1	19 s	Rock broken
60	1.02	194	1	45 s	PDC not broken
	1.27	194	1	45 s	PDC not broken
	1.52	194	1	25 s	Rock broken

Table 2 Results of PDC cutting square basalt bars in lathe

PDC anagle/(°)	Cutting depth/mm	Spin velocity/(r·min^{-1})	Feed velocity/(mm·r^{-1})	Cutting time	Notes
15	0.25	194	1	1 min and 30 s	PDC not broken
	0.51	194	1	1 min and 30 s	PDC not broken
	0.76	194	1	1 min and 30 s	PDC not broken
	1.02	194	1	1 min and 30 s	PDC not broken
	1.27	194	1	1 min and 30 s	PDC not broken
	1.52	194	1	1 min and 30 s	PDC not broken
	1.78	194	1	1 min and 30 s	PDC not broken
	2.03	194	1	1 min and 30 s	PDC not broken
	2.29	194	1	1 min and 30 s	PDC not broken
	2.54	194	1	1 min and 30 s	PDC not broken
	2.79	194	1	1 min and 30 s	PDC not broken
	3.05	194	1	1 min and 30 s	PDC not broken
	3.30	194	1	1 min and 30 s	Rock broken
30	0.25	194	1	1 min and 30 s	PDC not broken
	0.51	194	1	1 min and 30 s	PDC not broken
	0.76	194	1	1 min and 30 s	PDC not broken
	1.02	194	1	1 min and 30 s	PDC not broken
	1.27	194	1	1 min and 30 s	PDC broken
45	0.25	194	1	45 s	PDC not broken
	0.51	194	1	45 s	PDC not broken
	0.76	194	1	45 s	PDC broke
60	0.25	194	1	1 min	PDC not broken
	0.51	194	1	1 min	PDC not broken
	0.76	194	1	1 min	PDC not broken
	1.02	194	1	1 min	PDC broken

Table 3 Results of linear cutting of granite and concrete

Material	Cutting velocity /(mm·min^{-1})	Hydraulic pressure /MPa	Thrust (WOB) /N	Impact energy /J	Impact spacing /mm	Average depth /mm	Notes
Concrete	133	0.35	1401	0	0	0.570	No PDC broken
		0.53	2087	0	0	0.770	
		0.70	2793	0	0	0.970	
		1.05	4191	0	0	1.803	
		1.40	5588	0	0	2.302	
Granite	133	0.35	1401	0	0	0.060	Several PDCs broken
		0.53	2097	0	0	0.150	
		0.70	2793	0	0	0.310	
		0.84	3355	0	0	0.460	
		1.05	4191	0	0	0.410	
		1.40	5588	0	0	0.710	

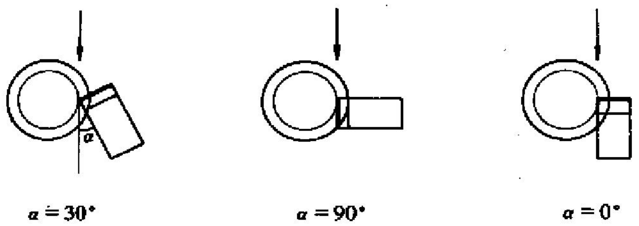

Fig. 3 Force withstood by PDC cutter at different cutting angles

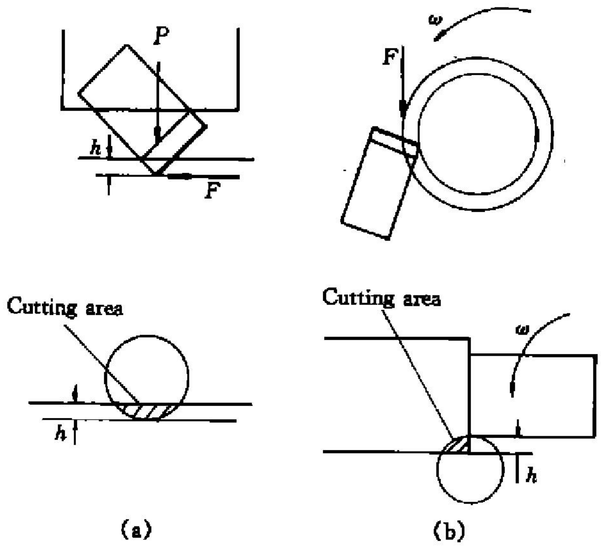

Fig. 4 Comparison between rotary drilling or linear cutting and cutting in lathe
(a) —Rotary drilling; (b) —Cutting in lathe

Comparing the results of granite with those of concrete in Fig. 5, it becomes apparent that the cutting depth of the PDC cutter in granite is much less than that in concrete. Furthermore, its increasing rate with WOB in granite is also much less than the rate in concrete. It is noted that for the strongest one in all the types of the PDC cutters tested, the experiments have verified that the critical value of the thrust (WOB) which corresponds to a PDC of frequent failure, is about 2 800 N in the very hard granite tested. On the other hand, the thrust of 2 800 N can only generate a cutting depth of about 0.3 mm in

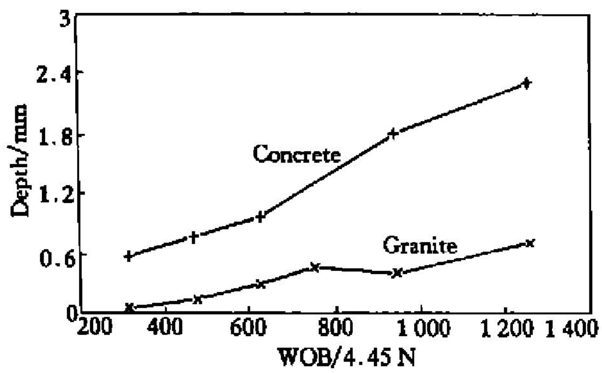

Fig. 5 Cutting depth as function of thrust (WOB)

the granite. It seems to conclude that the rotary drilling with flat PDC bits is not used in very hard rocks because the rate of penetration in rotary drilling is obtained mainly by increase in the thrust or WOB. In very hard rock, the increase of WOB will not only result in little variation in the rate of drilling or penetration, but also the larger cutting force induced by increasing WOB will no doubt produce a great possibility for shearing failure of PDC cutters. However, the experimental results also clearly show that rotary drilling of flat PDC cutters is very suitable for soft rocks. From Fig. 5 it can be seen that for concrete, not only can a low thrust (WOB) generate a relatively higher cutting penetration, but the cutting depth is very sensitive to the variation of WOB. In the meantime, even under the condition of high WOB values, no any PDC was broken.

3.3 Comparison between rough and smooth surfaces

Table 4 lists the results of the PDC linear cutting on the rough and smooth surfaces of the granite block. Because of faults and cracks existing in the rough surface, it should be inferred that the cutting resistance from the rough surface is less than that from the smooth surface. Therefore, the life of the PDC working on the rough surface should be longer than that on the smooth surface. However, it seems that this conjecture can not be verified by the results listed in Table 4. Table 4 shows that the cutting length of most of the PDC cutters on the rough surface was short, compared to the cutting length of the PDCs on the smooth surface. The reason may be that the impact of the rough surface on the PDC cutters counteracts an influence of the low cutting resistance because of faults and weaknesses.

4 CONCLUSIONS

1) Pure cutting of PDC on the cored rocks in a lathe has a small cutting area and very low cutting force generated only by rotation as compared with rotary drilling of PDC bits. Thus, this kind of cutting can not simulate the cutting action in actual rotary drilling of PDC bits.

2) As a comparison of the influence of different cutting angles on the cutting efficiency and ability of the cutters to withstand loads, it is feasible to machine off the layers of rock using the PDC cutters in a lathe.

3) For rock cutting breakage by flat PDC cutters, the cutting angles have a significant influence on the cutting capacity and life of PDC. The lower the cutting angle, the more effective the cutting action of the PDC cutters, with less damage to the PDC.

4) Rotary drilling of PDC cutters can efficiently used for soft rocks but single mode of rotary drilling

Table 4 Results of PDC cutting on rough and smooth surfaces of granite

PDC type	Surface feature	Hydraulic pressure / MPa	Static thrust (WOB) / N	Average cutting speed / (mm·min^{-1})	Total cutting length / mm	Notes
Long PDC	Rough	0.53	2 097	170	1330	PDC not broken
		0.84	3 355	170	116	PDC broken
	Smooth	0.53	2 097	204	1 348	PDC not broken
		0.84	3 355	176	575	PDC not broken
	Rough	0.70	2 793	202	1 173	PDC not broken
	Smooth	0.70	2 793	140	262	PDC broken
	Rough	0.70	2 793	140	815	PDC broken
	Smooth	0.70	2 793	140	958	PDC not broken
New long (α= 30°)	Rough	0.70	2 793	160	84.8	PDC broken
	Smooth	0.70	2 793	134	105.8	PDC broken
Short PDC	Rough	0.53	2 097	150	105.3	PDC broken
	Smooth	0.53	2 097	150	126.2	PDC broken
	Rough	0.53	2 097	146	20.0	PDC broken
	Smooth	0.53	2 097	146	74.2	PDC broken
	Rough	0.53	2 097	144	101.6	PDC broken
	Smooth	0.53	2 097	144	65.9	PDC broken

in very hard rocks will result in very low rate of penetration and frequent damage of PDC.

5) Impact induced by rough surface of very hard rocks can accelerate the damage of PDC cutters.

ACKNOWLEDGMENT

Test assistance provided by Mr. K. Lindquist and Mr. M. Balven is appreciated.

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(Edited by HE Xue-feng)