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Failure modes of PDC cutters under different loads①

LI Xi-bing(李夕兵)[1], ZHAO Fu-jun(赵伏军)[1], D. A. Summers[2], G. Rupert[2]
(1. Institute of Mining and Rock Engineering, Central South University, Changsha 410083, China;
2. Rock Mechanics and Explosives Research Center, University of Missouri-Rolla, MO65401, USA)

[Abstract] The capability of several types of flat PDC cutters to withstand combined loads were tested and evaluated by the impact and cutting of single PDC cutter on granite in a linear impact-cutting table. The primary failure modes of PDC cutters withstanding different combined loads were investigated and analyzed. The suggestions of enhancing PDC cutters to be suitable for drilling very hard rock have been made.

[Key words] failure mode; PDC cutters; combined loads
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1 INTRODUCTION

It is well known that polycrystalline diamond compact(PDC) bits can usually be used with success only in soft, soft-medium hard, and medium hard, non-abrasive formations[1~5]. In those formations, PDC bits can obtain not only a high rate of penetration but also a high footage. Usually, the reason why PDC bits have a limited use in very hard and abrasive rocks is largely attributed to the strong dependence of PDC failure on impacting loads used for breaking hard rock and the frictional temperature that develops at the cutter/rock interface because of the rock abrasiveness[6~8]. However, so far, details on failure modes of PDC cutters in very hard rocks can seldom be seen in referred technical literature. In order to obtain information about the failure modes and the capacity of withstanding loads of different types of the PDC cutters, a limited program of tests was undertaken which included impact, cutting, and a combination of impact-cutting. The failure modes of PDC cutters withstanding different combined loads in very hard rocks are analyzed and discussed in detail.

2 EXPERIMENTAL

The PDC cutters used in tests include three different sizes and structures of conventional flat PDC cylinder developed by Novetak company, as shown in Fig. 1. From Fig. 1(c) it is seen that the saw-contacted PDC means that the diamond layer is fixed with tungsten-carbide body in saw-shaped plane. Experiments of PDC cutters were performed in a linear multifunction table which can provide the PDC with static thrust, impact, and cutting. The principle of the table is 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, WOB) onto the rock. To provide the rock with an impact force through the PDC, a rod with hammer is used to impact the movable transmitted rod which is inserted through the thrust cylinder with an axially centre hole. The rod with a hammer can be raised and dropped by a ratchet device rotated by an electric motor, its raising or lowering height of the rod is 15.24 cm, its impact energy can be changed by increasing or decreasing the mass of the hammer. The impact spacing can be controlled by changing the cutting velocity or 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 penetrating the rock supplemetally.

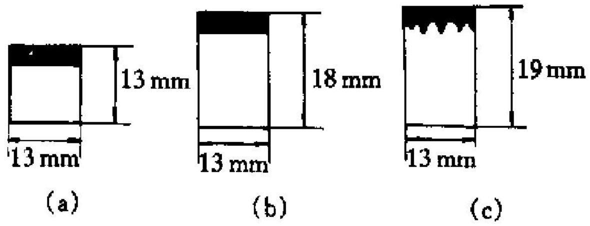

Fig. 1 Three kinds of flat PDC cutters
(a) —Short; (b) —Long; (c) —Saw-contacted

The rock tested was a block of Missouri red granite with a size of 500 mm. Its uniaxial compression strength is about 240 MPa. And the measured Schmidt rebound index is 43.5. In tests, PDC attacked the samples at an angle of 45° if no special notes was given.

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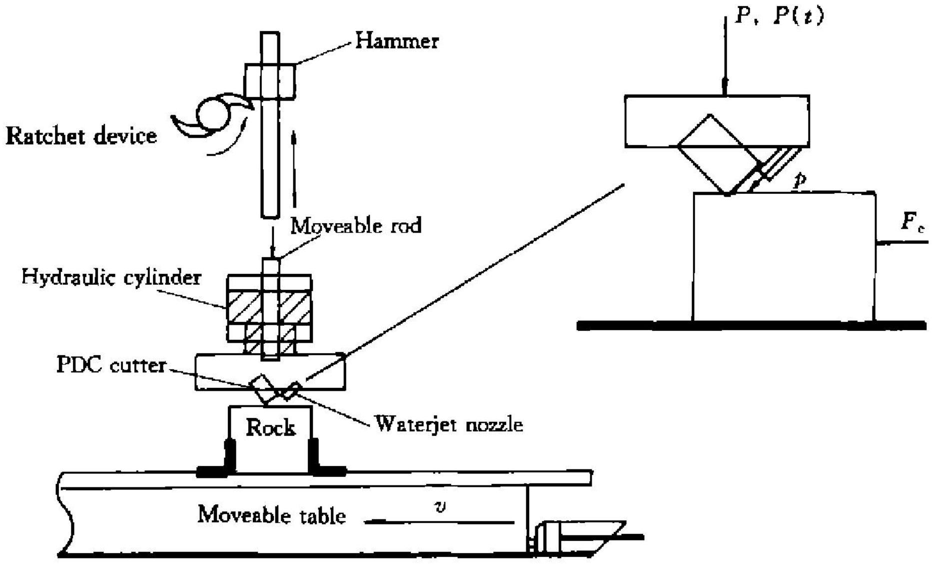

Fig. 2 Principle and layout of linear table

3 RESULTS AND DISCUSSION

3.1 Capability of PDC to withstand loads

The lab results on the capacity of three kinds of PDC cutters: short, long, and saw-contacted, to withstand different loads on the linear table are listed in Table 1 and Table 2. Table 1 and Table 2 show that for cutting the very hard, red granite used in the lab, which has an estimated unconfined compressive strength of 240 MPa, no matter what the type of PDC cutters are used, the maximum thrust (or WOB) of a single cutter should at best be less than 2 793 N. In the meantime, discontinuous impacts without static thrust can also result in the failure of PDC cutters. Thus, PDC cutters' cutting of very hard rocks under a combination of impact-static thrust will no doubt promote the failure of PDC cutters. However, from Tables 1, 2 it is likely that the ability of the new, long PDC to withstand loads in hard rocks is higher than those of the new, short and the old, long PDCs.

As a comparison, Table 3 lists the results of cutting the concrete block on the linear table. In all of the tests on concrete, even with a combination of a thrust of 5 588 N and an impact energy of 61 J, no PDC cutters were broken.

Why the penetration of the same type of PDC withstanding a very high impact- thrust combined load on concrete didn't result in the damage of the PDC is easily explained as followed. It is assumed that the thrust forces acting on the PDC cutters, cutting concrete and red granite, are both equal to 5 588 N. From Fig. 3 it is easily concluded that the reason why the PDC cutters were always broken in very hard rocks is that the cutting force F_c generated in very hard rock is much larger than that in soft rock for the same thrust (WOB).

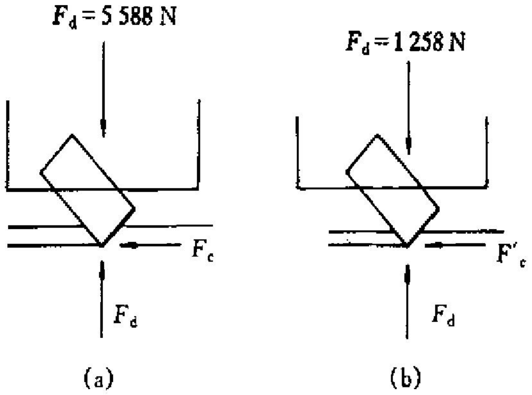

Fig. 3 Trust force and cutting force
(a) —Concrete; (b) —Red granite

It is noted that WOB is more than 130~ 180 kN in actual rotary drilling with PDC bits. The amount of PDC cutters in a bit is usually between 30~ 40, and the average thrust force of each PDC cutter reaches above 4 500 N. This is much larger than maximum WOB tolerance of the PDC cutters used in very hard granite. Therefore, rotary drilling with flat PDC cutters should be limited to soft to medium formations.

3.2 Primary failure modes of PDC cutters and suggestion

In the tests, it was found that the failure modes of PDC cutters included the following several forms shown in Fig. 4.

1) Axial shearing: it occurred when the static thrust force F_d was large. In this case, the PDC was broken mainly by increasing cutting force F_c. In the tests for red granite, when the thrust force (WOB) reached or was larger than 2 793 N, most of the PDC cutters were broken in the form.

2) Impact crushing: this failure of PDC cutters corresponds to a combination of a low static force F_d

Table 1 Capacity of PDC cutters to withstand loads in granite

PDC type	Hydraulic pressure/MPa	Thrust (WOB)/N	Impact energy/J	Impact spacing/mm	Cutting length/mm	Cutting depth/mm	Notes
Short 1	0.70	2 793	33.9	13	< 200		1# PDC broken
Short 2	0.70	2 793	0	0	< 250		2# PDC broken
Long 1	7.00	27 940	0	0	< 5		1# PDC broken
Long 2	3.50	13 970	0	0	< 5		2# PDC broken
Long 3	3.15	12 573	0	0	< 5		3# PDC broken
Long 4	1.75	6 985	0	0	< 10	1.16	4# PDC broken
Long 5	0.70	2 793	33.9	12.77	430		5# PDC broken
Long 5	0.70	2 793	0	0	500	0.33	5# PDC broken
Long 6	0.70	2 793	0	0	750		6# PDC not broken
Saw 1	1.40	5 588	0	0	59	0.63	1# PDC broken
Saw 2	1.40	5 588	0	0	29	0.80	2# PDC broken
Saw 3	1.05	4 191	0	0	12	0.41	3# PDC broken
Saw 4	0.84	3 355	0	0	209	0.48	4# PDC not broken
Saw 4	0.84	3 355	61.0	0.72	54		4# PDC broken
Saw 5	0.84	3 355	61.0	0.69	< 135*		5# PDC broken
Saw 6	0.84	3 355	0	0	17	0.42	6# PDC broken
Saw 7	0.70	2 793	0	0	774	0.31	7# PDC broken

* Attack angle is 60°

Table 2 Capacity of PDC cutters to withstand long term discontinuous impacts in granite

PDC type	Hydraulic pressure/MPa	Thrust (WOB)/N	Impact energy/J	Impact spacing/mm	Consecutive impact times	Notes
Long 7	0	0	23.7	7.4	13	7# PDC broken
Long 8	0	0	23.7	7.4	101*	8# PDC not broken
Long 9	0	0	23.7	7.4	19	9# PDC broken
Saw 10	0	0	33.9	11.0	41	10# PDC broken
Saw 11	0	0	33.9	6.6	37	11# PDC broken
Saw 12	0	0	23.7	7.2	23	12# PDC broken
Saw 13	0	0	33.9	Changed	71	13# PDC not broken

* Attack angle is 60°

Table 3 Results of cutting concrete on linear table

Pressure /MPa	Thrust (WOB)/N	Impact energy/J	Impact spacing/mm	Average depth/mm	Notes
0.70	2 793	33.9	7	2.98	PDC not broken. Test was done on the same side of the concrete
0.70	2 793	33.9	18	2.29	
0.70	2 793	33.9	30	2.23	
0.70	2 793	33.9	40	2.40	
0.70	2 793	33.9	50	2.65	
1.40	5 588	33.9	6	5.06	
1.40	5 588	33.9	20	2.67	
1.40	5 588	33.9	55	2.56	
1.40	5 588	61.0	22	3.01	
1.40	5588	0	0	1.58	The other side of the concrete block, PDC not broken.
1.40	5 588	0	0	1.78	
1.40	5 588	61.0	16	2.09	
1.40	5 588	61.0	25	2.14	

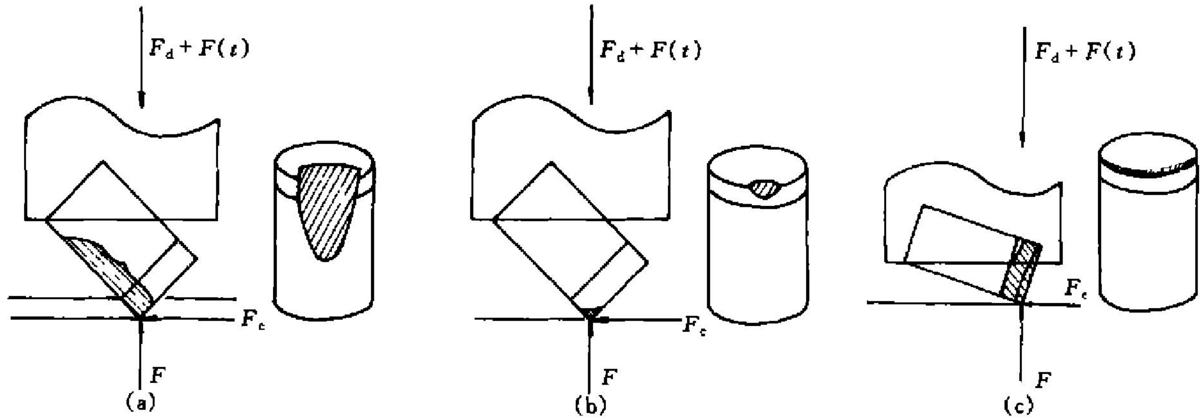

Fig. 4 Failure modes of PDC cutters
(a) —Axial shearing; (b) —Impact crushing; (c) —Radial shearing

and a high impact force $F(t)$ under a 45° attack angle. Because of the low static thrust force, the cutting force is not large. The PDC is broken mainly by the impact compressive force.

3) Radial shearing: radial shearing usually took place under the condition of a small attack angle and a low static thrust force. It is also usually caused by a strong impact.

Therefore, PDC cutters should be enhanced in two ways to help withstand loads including impact, static thrust, and cutting, while maintaining their cutting function. One is increasing the strength of the diamond layer and tungsten-carbide substrate, especially the shear strength of the TC body. Another is changing the geometry of the PDC cutters. It is suggested that the PDC flat cutters widely used in rotary drilling be adjusted to the diamond-enhanced inclined chisels as shown in Fig. 5.

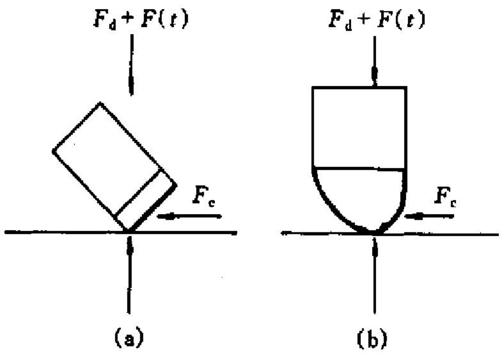

Fig. 5 Suggested enhancement of geometry of cutters
(a) —Flat PDC cutter;
(b) —Diamond-enhanced inclined chisel

4 CONCLUSION

From the above results and discussion it is reasonably concluded that single rotary drilling with PDC flat cutters is not suitable for very hard formations. This is because the footage of the rotary drilling is obtained mainly by increasing thrust force (WOB). However, in very hard rock, increasing the WOB will not result in a large variation in the depth of penetration but a significant increase of the cutting force which results in a shearing failure of the PDC cutters. Although the test results suggest that the percussive rotary drilling with flat PDC cutters can greatly increase the rate of penetration in hard formations, the great cutting force induced by a strong impact and static thrust will make the PDC cutters damage in the form of axial shearing.

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