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Penetration and impact resistance of PDC cutters inclined at different attack angles①

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Abstract: In order to develop a rotary-percussive bit with diamond-enhanced cutters assisted by high pressure water jets, it is necessary to study the damage mechanism and the penetration properties of PDC cutters subject to different impact load level and rock types. Therefore the impact experiments of the single PDC cutters with different attack angles in four rocks: black basalt, Missouri red granite, Halston limestone, and a very soft (Roubidoux) sandstone were carried out, and the effects of rake angles of PDC cutters on both the penetration and impact resistance of PDC cutters have been discussed in detail. Test results show that a PDC insert can withstand a very strong impact in compression but is easily damaged by impact shearing, the PDC cutters are more easily damaged by shearing if the attack angles are relatively small, the 45° PDC cutters have the least penetration resistance among the cutters tested. Thus it is suggested that the attack angles of PDC cutters should be larger than 30° for bits which must withstand impact from a hammer.

Key words: PDC cutters; penetration and impact resistance; rotary-percussive drill bits **Document code:** A

1 INTRODUCTION

Since the introduction of polycrystalline diamond compact (PDC) bits in the mid-1970's, these tools have gained increasingly wide acceptance. This is not because of the tool itself, but also because of the advances that made in the materials used to form the bits and in the bit designs themselves. Generally, PDC bits have been proved successful for use in drilling formations ranging from soft to medium hard, and where the rock is nonabrasive[1]. The reasons which limit PDC use in harder formations are that PDC cutters have the two basic performance limits: the maximum threshold impact force that can be sustained and a thermal limit that dictates wear rate[2,3]. 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[4]. Hence for this tool to expand its useful horizon, new concepts need to be developed which will enable PDC inserts to successfully drill in hard and abrasive rock. Such a study should be in addition to improving the inherent properties of PDC materials to increase the level of the impact resistance of these cutters. It is noted that a PDC has an extremely high compressive strength . Using PDC in a combined action mode with crushing, shearing, and complete cleaning of the crushed zone would minimize bit sensitivity to heat and take advantage of its great compressive strength. So potentially, developing a rotary-percussive bit with diamond-enhanced cutters assisted by high pressure water jets is an answer.

A number of studies on PDC inserts have been used for rotary drilling, laboratory and field tests have investigated the effects at different rake angles with single and multiple point cutters to evaluate performance[5,6]. It is now known that as the back-rake angle is decreased the cutting action becomes more efficient, i.e., for the same weight on bit (WOB), a greater depth of cut is achieved with a smaller back-rake angle, which generally produces a larger chip. This makes the bit more aggressive and, other things being equal, a higher result of penetration is attained. But when a PDC rotary-percussion bits is designed for very hard formations, such data are not evident yet. The extent to which the rake angle affects the crushing action of the cutters, and how it allows the insert to withstand the impact from the hammer blows must be identified. From such studies one can decide what is a reasonable rake angle at which impact rock fragmantation can be most efficient. Of equal or greater importance is, on the other hand, which rake angles will make the cutter more vulnerable to impact damage.

In this study impact experiments were carried out using a single PDC cutter set at different attack angles. The tests were conducted on four rocks: black basalt , Missouri red granite, Halston limestone and a very soft (Roubidoux) sandstone. Objectives of the experiments reported here were to investigate the

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effects of the rake angle of PDC cutters on both the impact resistance of the PDC insert and crushing action or penetration depth.

2 EXPERIMENTAL APPARATUS AND PROCEDURES

2.1 Incident impact energy

For the impact experiments with a single cutter, the impact system should have the capacity to provide the cutter with enough incident energy to guarantee that the cutter will penetrate the rock. Earlier research has shown that the specific energy required to penetrate very hard rock using percussive drilling is greater than 600 J/cm^3, in hard rock the limit is about 400 J/cm^3, and for very soft rock below 200 J/cm^3[7]. For a single PDC cutter, assuming the penetration depth per a blow is 5 mm, the estimated fragmented volume is about 0.5 cm^3. The impact energy required to break hard rock of 0.5 cm^3 is about 200 J. Hence the experiment apparatus should be able to produce an impact energy of 200 J more or less.

2.2 Design of hammer geometry

In impact experiments there are two methods for increasing the impact energy. One is by using a very heavy hammer with a diameter greater than that of the drill rod. This will produce an incident wave with a relatively long duration. Fig.1, for example, is a theoretical waveform produced by the impact of a 25 kg hammer on a rod with a diameter of 35 mm. The alternative approach is by raising the impact velocity or drop height for the hammer with a fixed weight. In an effort to separate the reflected waves from the incident waves the best choice is the second, i.e. by increasing the impact height for a fixed hammer weight. In the equipment design chosen, the length of transmission rod is about 1.2 m between the hammer and the insert. Thus the incident wave duration should be limited to about 150 μs so that the reflected waves can be superimposed on the incident waves. For this same reason, the designed hammer was made up of a cylinder with the same diameter as the rod. The length of the hammer is 40.6 cm, the calculated duration is about 140 μs. The weight of the hammer is 3.08 kg. The planned impact heights are 609.6, 426.7 and 243.8 cm respectively, which have a corresponding impact energies of 184.0, 128.9 and 73.7 J.

2.3 Experimental apparatus

The layout for the experimental apparatus is shown in Fig.2. The transmission rod is connected to the indenter through a bolt which will guarantee that the reflected tension pulses can be transmitted into the rod. The PDC cutters are tightly inserted into the indenter at different angles as shown in Fig.3 so that

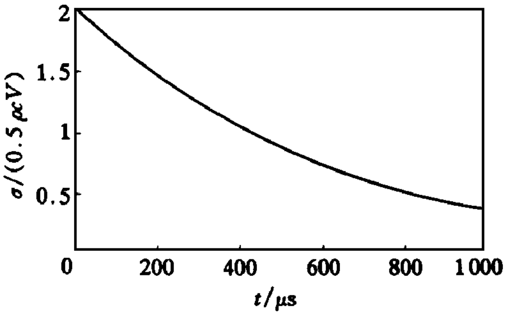

Fig.1 Stress wave generated by impact of a 25 kg hammer on a d35 mm rod

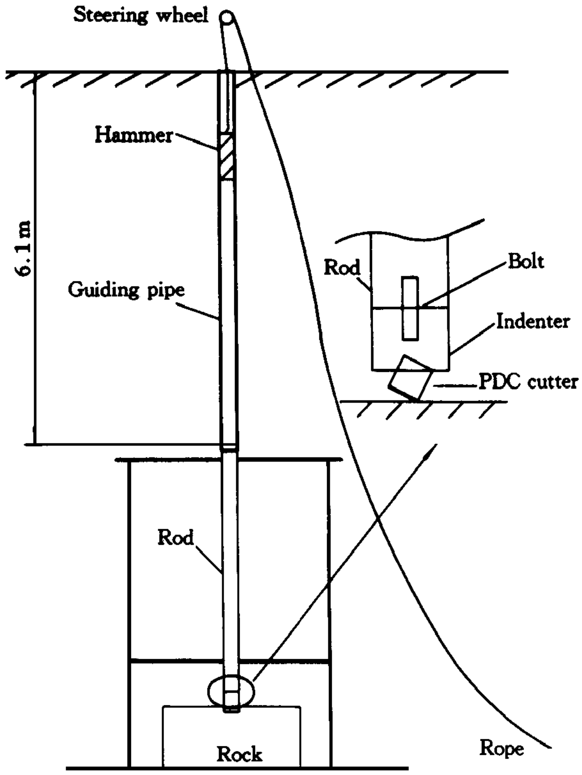

Fig.2 Layout diagram of hammer-drop apparatus

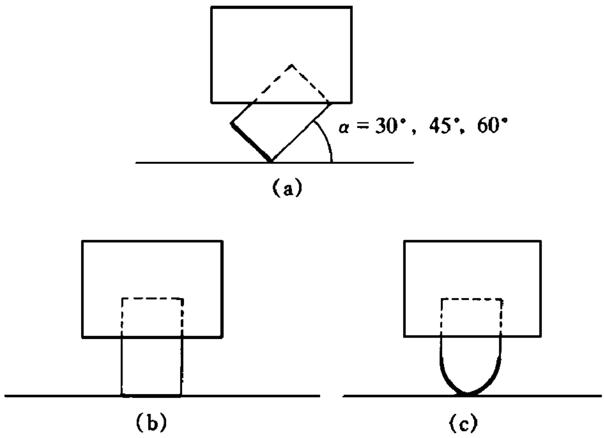

Fig.3 PDC cutters with different attack angles
(a) —Inclined PDC; (b) —Vertical PDC; (c) —Vertically domed PDC

the impact and penetration resistance of PDC cutters at these different attack angles can be tested on rock. Pairs of diametrically opposite and axially oriented strain gauges were mounted externally on the middle of the rod, about 600 mm from the interface between the rock and the cutter. Theoretically the incident wave for each of the experiments should be rectangular. But the incident waveforms sometimes had a serious distortion because of difficulty in controlling the exact direction of the hammer at the instant of axial impact with the rod.

2.4 Rock samples and test procedures

Rock samples tested included a very hard black basalt, Missouri red granite, Halston limestone and a very soft, seriously weathered sandstone. After each blow, the penetration depth was measured and both the incident and reflected waves were recorded. Because of the recognized heterogeneity of the rock samples and random errors produced in the test process, ten tests were run at each condition. This also provided a better statistic average penetration depth for each of the rock samples tested at any fixed impact energy level and PDC cutter angle.

3 EXPERIMENTAL RESULTS

3.1 Penetration resistance or depth of PDC cutters

The experimental results showing the influences of both impact energy and attack angle on the penetration depth of a single PDC cutter into the variety of rock tested are shown in Table 1 and Fig.4. A domed cutter was also included in the test program.

From Table 1 and Fig.4, it can be seen that the penetration depth increases with greater impact energy. The penetration depth achieved in basalt, granite and limestone is roughly similar under the same impact energy and PDC cutter angle. The penetration achieved in sandstone is much larger than this. The reason why sandstone has a greater depth of penetration is that the sandstone tested in the experiment

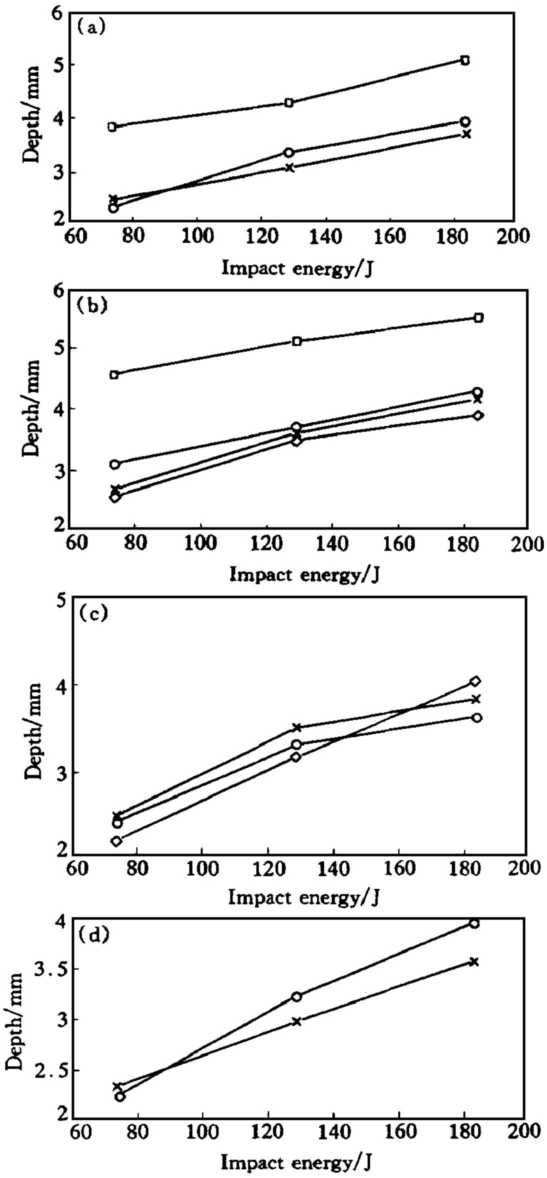

Fig.4 Effects of incident impact energy on penetration depth
(a) —30°; (b) —45°; (c) —60°; (d) —Domed button
□ —Sandstone; ○ —Granite;
× —Limestone; ◇ —Basalt

Table 1 Average penetration depth of single cutters (mm)

Rock types	Energy level/J	PDC cutter attack angles				
		30°	45°	60°	90° domed	Averages
Granite	73.7	2.330	3.098	2.402	2.232	2.515
	128.9	3.349	3.685	3.273	3.208	3.379
	184.1	3.934	4.307	3.615	3.948	3.951
Basalt	73.7		2.536	2.173		2.355
	128.9		3.481	3.147		3.314
	184.1	3.699	3.896	4.007		3.867
Limestone	73.7	2.462	2.677	2.464	2.324	2.482
	128.9	3.058	3.594	3.468	2.961	3.270
	184.1	3.715	4.155	3.801	3.556	3.807
Sandstone	73.7	3.827	4.538			4.812
	128.9	4.264	5.089			4.676
	184.1	5.093	5.506			5.299

was seriously weathered and the rock strength is correspondingly very low. It is noted that the penetration depth of indenter is frequently used as a drillability index from which one can evaluate the penetration resistance of the rock to drilling[8]. Thus a deeper penetration depth means that the penetration resistance is smaller and the rock is correspondingly easier to drill under equivalent impact energy. Basalt's penetration resistance is the largest among the rocks tested, although the penetration resistances of limestone and granite are quite similar.

Fig. 5 is the plot of the experimental results showing the influence of attack angle on the penetration depth. The plots clearly show that the penetration depth obtained using a 45° attack angle is the largest. The reason that 45° angle provides the PDC the greatest ease in penetrating into rock can be explained due to PDC's geometry and the force withstood by the rock under the cutter.

3.2 Impact resistance of PDC cutters

Table 2 shows the number of impacts which the PDC cutters withstood at different attack angles and total impact energy to which each PDC cutter was experienced before each PDC cutter showed significant damage. From Table 2, it is easily discerned that the impact resistance of PDC cutters will be greater at larger attack angles. In these tests the 30° inclined PDC cutters were more easily broken than the other PDCs. In order to demonstrate whether a PDC insert is easy to break under impact compression, a 90° oriented PDC cutter, as shown in Fig.3(b), was placed on a basalt sample and subjected to 30 blows at the energy level of 184 J. No damage was found on that PDC cutter. These experimental results are easily explained when one considers the force distribution within a PDC cutter at the different attack angles.

When the attack angle is decreased, the lateral shearing force acting on the PDC will increase. When the attack angle is changed to 90° the lateral shearing force becomes zero and the PDC is required to withstand pure longitudinal impact compression. As the PDC generally has an extremely high compression strength and a low shear strength, the damage to which the PDC cutter is subject will change with attack angles. All of the 30° PDC inserts tested were finally damaged by spalling, while the 60° PDC inserts were mainly damaged by crushing.

4 DISCUSSION AND CONCLUSIONS

1) Tests have shown that a PDC insert can withstand a very strong impact in compression but is easily damaged by impact shearing. In order to operate at angles below 45° degrees the PDC material may need to be improved both structurally and in geometry in an effort to make the bits better able to withstand the impact load from a hammer drill.

2) 45° PDC cutters will likely see the least penetration resistance and as a result will be able to achieve a high penetration depth than other insert angles, and this insert angle will be more aggressive in drilling by crushing rock by impact.

3) The results of the impact resistance testing of the PDCs show that the PDC cutters are more easily damaged by shearing if the attack angles are relatively small. The suggested attack angles of PDC cutters are larger than 30° for bits which must withstand impact from a hammer.

4) Experiments showed that the indentation of the cutters under hammer impact will produce a lot of consolidated rock powders under the cutter. Research has shown that the reconsolidation of these crushed rock powders consumes a part of incident energy[9]. To increase penetration efficiency the crushed rock should be washed or blown out. This will be studied more in the combined drag & impact tests which follow.

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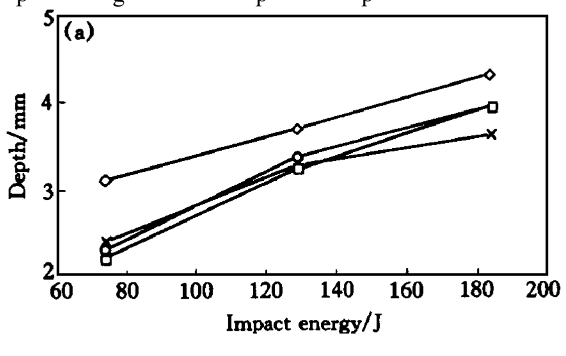

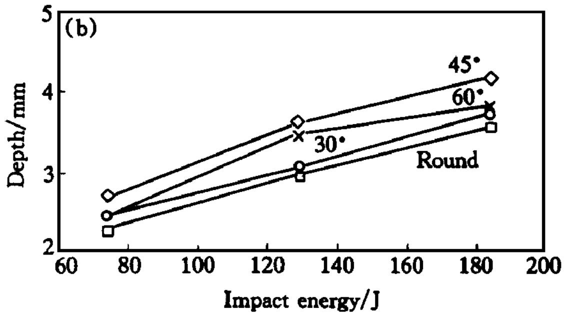

Fig.5 Effects of attack angle of PDC cutter on penetration depth

(a) —Granite; (b) —Limestone

◇—45°; ○—30°; × —60°; □—Domed

Table 2 Impact resistance of PDC cutters

PDC number	Attack angle/(°)	Impact energy per a blow / J	Impact times	Rock types	Total energy/ J	Final results
3	30	128.9	4	Granite		
		184.1	3	Granite	1 068	Damaged by spalling
4	30	184.1	10	Granite		
		184.1	4	Basalt	2 577	Damaged by spalling
8	30	184.1	10	Limestone		
		128.9	10	Limestone		
		73.7	10	Limestone		
		184.1	3	Basalt	4 418	Damaged by spalling
7	30	184.1	5	Basalt	921	Damaged by spalling
10	30	184.1	1	Basalt	184	Damaged a little
1	45	184.1	10	Granite		
		128.9	10	Granite		
		73.7	10	Granite		
		184.1	1	Basalt		
		73.7	9	Basalt		
		128.9	5	Basalt	5 356	Damaged
2	45	184.1	10	Basalt		
		128.9	5	Basalt		
		184.1	10	Limestone		
		128.9	10	Limestone		
		73.7	10	Limestone		Not damaged
5	60	184.1	10	Granite	1 841	Damaged a very little
6	60	184.1	10	Basalt		
		128.9	10	Basalt		
		73.7	10	Basalt		
		128.9	2	Granite	4 125	Damaged a little
9	60	128.9	8	Granite		
		73.7	10	Granite		
		73.7	10	Limestone		
		128.9	10	Limestone		
		184.1	10	Limestone		
		184.1	9	Basalt	7 292	Damaged
11	90	184.1	30	Basalt		Not damaged
12	90(domed)		All tests all tests	Granite limestone		Not damaged

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