Study on rock breaking efficiency of special shaped cutters

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Abstract. The optimization of cutter shape has become one of the main innovation direction of PDC bit technology. At present, both domestic and foreign bit manufacturers have put forward various special shaped cutters to improve rock breaking efficiency. However, there are relatively few researches which focus on the rock breaking efficiency of special-shaped cutters. Therefore, three kinds of typical cutters (flat cutter, convex cutter and concave cutter) are selected as the study object in this paper. Based on the single cutter test, the relationship of axial cutting force, cutting area and cutting specific energy under different working conditions will be provided. The experimental results show that the axial cutting force and specific energy of concave cutter and convex cutter are lower than that of flat cutter in most test cases. The results are almost the same for both Vosges sandstone and Marcellus shale cases. In other words, the tested concave cutters are easier to intrude into rock and obtain higher rock breaking efficiency under the same cutting conditions, when compared with flat cutter and convex cutter. The experimental method provides a technical reference for studying the rock breaking efficiency of three-dimensional cutters with different shapes.

1. Introduction

As the key cutting element of PDC bit, the performance of polycrystalline diamond compacts (PDC) directly determines the quality of PDC bit. With the improvement of the material composition and manufacturing process of PDC layers, traditional PDC cutters are gradually becoming suitable for hard formations from only soft to medium hard formations [1]. However, the follow researchers found that conventional flat PDC cutters do not always maintain high cutting efficiency in all available formations. So, some special shaped cutters are proposed to improve the rock breaking efficiency for different lithology.

2. PDC cutters

In 1971, General Electric (GE) invented polycrystalline diamond compacts (PDC), the conventional cylindrical-planar cutters, as shown in Figure 1, and applied them to oil drilling bits. In 1980, GE and Mega Diamond proposed to use silicon impregnation combined with polycrystalline diamond to improve the thermal stability and impact resistance of PDC [2]. In 1986, Smith Company used Co diffusion impregnation method to synthesize PDC material, which solved the graphitization problem of diamond surface and improved its wear resistance [3]. Hycalog used a cobalt filtration process to increase the temperature of the PDC to 1200 °C, which increasing its thermal stability.
Honeycomb Structure Diamond Composites dramatically improve impact resistance and toughness [4-5].

In the nearly 50 years, the researchers greatly improve the impact resistance, toughness, abrasion resistance and thermal stability, of PDC from the material composition, structure and manufacturing technology which also greatly improve the working hours and efficiency of PDC bit. Until now, the market share of PDC bit gradually increased and exceeded the absolute share of roller cone bit.

Figure 1. Profile of polycrystalline diamond compacts.

In recent years, with the rapid development of exploration and development technology of unconventional oil and gas resources (shale oil and gas, tight oil and gas, etc.), the drilling of deep and ultra-deep formation is facing many challenges and problems. Especially when drilling with hard/super hard formation, super wear-resistant formation and interlayer with big difference between soft and hard, the normal plane cutters will appear the abnormal failure of cutters such as cutter breaking and delamination, which seriously restrict the drilling speed and efficiency of deep and super deep Wells. In order to effectively improve the rock-breaking efficiency of PDC, the drill manufacturers and technical researchers have developed a series of non-planar cutters through optimizing the manufacturing and processing technology of PDC cutters and have made breakthroughs in the structure design of the cutter [6]. Schlumberger developed Hyper Blade cutter, axe blade cutter, stinger cone teeth, Onyx360 rotary cutter, Halliburton's Geometrix 4D special-shaped cutter, staycool cutter of Baker Hughes Company, convex triangular pyramid cutter developed by Houston Research Center of CNPC, etc [7].

2.1. Hyper blade cutter
The hyperbolic cutter design can effectively improve the rate of penetration (ROP) and has a good adaptability in plastic formations (Figure 2). In both soft and plastic formations, due to the heavy cuttings generated by cutters, the cutting efficiency of PDC bits can be affected when long cuttings enclose the cutting structure of the bit. Compared to flat PDC bit, the Hyper-Element uses hyperbolic geometry to create smaller cuttings, which can minimize ball-forming and prevent bit cutters from bit balling. This resulted in an average ROP increase of more than 21% for the Hyperblade bit [8].

Figure 2. Schlumberger's hyper blade cutter.

2.2. Axe blade cutter
Axe blade cutter provides a new way of rock breaking with its unique ridge geometry: the combination of shear rock breaking and extrusion rock breaking (Figure 3). Compared with traditional PDC bit, axe blade bit has higher ROP, and its drilling footage can be increased by at least 22% under the same weight of bit (WOB) and rotating speed. Axe blade's axe structure makes the thickness of the surface mounted diamond clad laminate about 70% thicker than that of the traditional cutting cutter, which leads to its stronger positive impact resistance. This feature improves the stability and wear resistance.
of the bit and can maintain the highest ROP throughout the drilling process. Field tests show that the ROP of axe blade bit can be increased by at least 29% compared with the bit based on PDC cutters, which is of great significance in improving drilling efficiency and reducing drilling cost [9].

![Schlumberger's axe blade cutter](image)

**Figure 3.** Schlumberger's axe blade cutter.

### 2.3. Sting blade cutter

The conical design of cutter makes the drilling load highly concentrated on the rock, further improving the drilling efficiency (especially for hard rock); At the same time, the upgrading of cutters diamond matrix also improves the impact resistance and wear resistance of the bit. The modification of matrix and cutter improves the drilling footage and ROP of sting blade bit in complex formation. The drilling work has no pressure even in hard formation, transition formation and gravel formation that conventional PDC bit is difficult to cope with. At present, sting blade bit has been applied for more than 250 times in 14 countries around the world (Figure 4). Compared with conventional bit, the average drilling footage can be increased by 55% and ROP can be increased by 30% [10-11].

![Schlumberger's Sting Blade cutter](image)

**Figure 4.** Schlumberger's Sting Blade cutter.

### 2.4. ONXY360 cutter

Through 360° rotation, heat and wear can be dispersed, which greatly improve the cutter and bit life – durability (Figure 5). Locating in the highest wear zone of the bit structure, the bit using the entire circumference of the cutting edge cuts through the formation, rather than leaking a fixed area outside the cutter. The 360° rotary action keeps the blade sharper, longer, and prolongs the use of the composite blade, and far exceeds the life of a conventional flat-cutter PDC bit [12].

![Schlumberger's ONXY360 cutter](image)

**Figure 5.** Schlumberger's ONXY360 cutter.

### 2.5. Geometrix 4D cutter

Geometrix 4D PDC bit with profiled cutter is designed to provide greater rock breaking efficiency by reducing chip flow, friction and thermal degradation (Figure 6). A series of unique geometric structures together with the traditional cylindrical composite compacts, can be applied in special conditions according to the needs of users, such as meeting the needs of long-life directional drilling under very harsh conditions. The main features of the bit design include: reducing the heat accumulation at the tool tip, faster cutting speed, effective ROP, and minimum wear under the same working conditions according to the characteristics of the composite [13].
2.6. StayCool cutter

StayCool cutters contribute to rock breaking efficiency and lower drilling costs by reducing composite cutting friction and increasing ROP. The StayCool composite features a unique non-planar diamond cutting structure to enhance performance in critical zones (Figure 7). In harsh drilling environments, such as sandstone and carbonate interlayers, the composite technology and heat resistance directly affect the performance of the drill bit. StayCool composite technology reduces heat generation at the cutter-rock interface, prolongs composite life, and thus extends composite cutting time, reduces the number of trips the bit makes, and shortens the total time to drill depth [14-15].

2.7. Convex triangular pyramid cutter

Convex triangular pyramid cutters are used to solve the technical problems of cutter fracture when drilling in hard and super hard formations (Figure 8). In the new non-planar cutter’s design, the part where the cutting cutter interacts with the formation is designed as a three-dimensional non-planar, and the top diamond layer is divided into three inclined planes, separated by three convex ridges. In the process of PDC bit cutter arrangement, one of the convex ridges is placed at the cutting edge, which is used as the tool surface for the bit to cut the formation. The traditional surface cutting is optimized to the rock breaking mode of point fracturing, line cutting and surface extrusion, so as to greatly improve the rock cutting efficiency of the bit [16].

3. Failure criterion of rock

3.1. Rock failure process

Generally, the failure of rock happens when the external load exceeds the limit that it can bear. The failure of rock due to instability occurs at some point after the peak load, and this is the damage process of rock. The damage process of rock is generally described by its stress-strain curve, as shown in Figure 9. For isotropically strengthened elastic-plastic materials, the damage itself shows as two forms: softening of yield stress (De) and decreasing of elasticity ((1-D)E). The solid line in the figure represents the stress-strain response after damage, while the dotted line represents the stress-strain response without damage. The response after damage is dependent on the size of the element. In the process of cutting, the rock is damaged when the plastic strain reaches a certain value, and the
resistance of the rock is weakened with the continuous increase of the plastic strain. When the plastic strain reaches the equivalent plastic strain and the complete failure occurs, the rock element falls off from the rock body [17-18].

Figure 9. Stress-strain curve of asymptotic damage of rock.

The whole process of rock damage stress-strain curve is generally divided into four stages. The first stage is the initial damage stage in the rock, some small cavities and weak media in the rock are compacted under the action of external force. In this stage, the stress and strain change non-linearly, the circumferential stiffness of the rock increases gradually, the main initial damage in the rock closes, and the linear elastic damage stage begins. The second stage is the elastic damage and deformation stage. In this stage, the stress-strain presents linear elastic change, the damaged area inside the rock begins to connect, and micro-cracks begin to occur. With the increasing of external load, the micro-cracks in the rock are increasing, and the material enters the stage of elastoplastic damage, that is, the crack generation and the stable expansion of macro cracks. When the rock damage continues to expand, the micro-cracks in the rock body are connected to each other, and the damage zone at the tip of each micro-cracks continues to expand. The stress here is the critical value of crack damage. When stress value is higher than the crack damage threshold, the rock will enter to the next stage, which is the crack continued evolution and unstable macro crack extension stage. When the stress value reaches the peak stress, the stability of crack extension will accelerate, after the rock into the yield stage, the crack inside of the rock expands rapidly. At this point, the damage increases exponentially, while before the peak strength, the damage evolution of the rock increases linearly, and the rock begins to fail as a whole [19].

3.2. Evaluation index

Triaxial force. During drilling, the cutter is affected by axial, tangential and radial forces. The axial force represents the ability of cutter to invade formation. The smaller the axial force required under the same cutting depth condition, the stronger the invading ability of cutter. Otherwise, it means that the invading ability of cutter is poor, and the spatial layout of the cutters needs to be optimized and adjusted. The tangential force represents the difficulty of rock breaking by the cutter. The smaller the tangential force is, the more easily the rock is broken. At the same time, the less tangential force the cutters have, the less torque the PDC bit requires, which helping to reduce stick-slip. The radial cutting force is the fundamental cause of the transverse vibration of the drill bit. The smaller the force, the better. Therefore, the bit design generally does not set the side rotation angle, and the radial force of the cutter is almost zero.

Specific Energy. In fact, it is a very complicated and changeable process for cutter to break rock. How to break more rock with less energy consumption has always been the goal of faster drilling. In engineering, Specific energy is used as an important parameter to measure the rock breaking efficiency of cutter. The Specific energy is the cutting energy by per unit volume rock, and its mathematical expression is:

\[
\text{MSE} = \frac{W_r}{V_{cut}}
\]

Where, \(W_r\)-- Specific energy by rock breaking; \(V_{cut}\)-- cutting volume of cuttings, mm³.
4. Single cutter test

4.1. Single cutting test bench

Single Cutter tests (SCT) are conducted by making a groove at constant depth of cut in rock samples that can be 15.2 cm long with a diameter of 20.3 cm (Figure 10). The rock sample is held in a pressure vessel with constant confinement pressure (up to 79.98 MPa), and, for permeable rock, pore pressure (up to 79.98 MPa). Tests can be conducted without flow rate but with different type of mud and with a mud pressure varying from 0 to 79.98 MPa. The maximum vertical force is 50 kN and the maximum radial and tangential forces are 20 kN. The rotary speed can vary from 0 to 300 rev/min and the Rate of penetration from 0 to 36 m/hr. Normal, drag and side forces are measured by a load cell just above the cutter.

Standard tests are conducted with constant ROP and rotation speed. Data for each test are collected and recorded on a computer at a sampling rate of 1000 Hz.

![Single cutter test bench](image)

**Figure 10.** Single cutter test bench.

4.2. Cutters

Three types of cutters were tested (Table 1): one flat cutter, one convex cutter and one concave cutter.

| Flat Cutter | Convex cutter | Concave Cutter |
|-------------|---------------|---------------|
| ![Flat Cutter](image) | ![Convex Cutter](image) | ![Concave Cutter](image) |

**Table 1.** Three types of cutters.

4.3. Rock samples

Two rock (Table 2) was used during the testing program.

| Uniaxial Compressive Strength (UCS) |
|------------------------------------|
| Vosges Sandstone                   | 40 MPa |
| Marcellus shale                    | 40 MPa - 60 MPa |

**Table 2.** Two rock sample.
4.4. Test plan and basic parameters

Table 3 shows the testing parameters of the test. Before the test, it was planned to test both rocks with the same drilling parameters (those of the Vosges Sandstone). Unfortunately, the cutting forces were higher than expected in the Marcellus Shale and it was decided to reduce the max DOC to 1.75 mm/rev.

Table 3. Set the basic test parameters.

| Parameter          | Value                                                                 |
|--------------------|------------------------------------------------------------------------|
| Confining Pressure | 40 MPa                                                                 |
| RPM                | 120                                                                    |
| Back rake angle    | 10, 17.5                                                               |
| DOC (mm/rev)       | Sandstone: 0.5, 1, 2, 4 \nShale: 0.5, 1, 1.5, 1.75                                               |

4.5. Test procedure

For each test, we have followed the same testing procedure: mount the rock sample, clamp the rock sample on the plate, screw the cutter on the drilling shaft, close the pressure vessel, fill the pressure vessel with oil, increase confining and mud pressures to the needed pressure, configure the SCT to the needed Rate of Penetration, start the rotation at 20 rpm, start data acquisition, push the cutter to the rock sample, push the drilling shaft at the needed ROP, do the test, stop the test, pull the bit from the rock sample, stop data acquisition, stop rotation, decrease confining and mud pressure, dismantle the pressure vessel, dismantle the rock sample, clean.

A huge amount of data is available and we have decided to present the experimental results through two series of curves. The first series curves are of normal force versus cutting area for all the depth of different shape cutters. It allows a direct comparison of DOC effect, groove deepening effect and cutting performance. The second series curves are specific energy versus cutting area for all the depth of different shape cutters. It allows a direct comparison of cutting efficiency.

5. Experiment result analysis

The curves in Figure 11(a) ~ 11(d) show the relation between axial cutting force and the cutting area by Vosges sandstone. The cutting experiment is under 40MPa confining pressure, 120rpm rotary speed and 10° back angle (BA). It is obvious that in Figure 11(a) ~ 11(c), the axial cutting force of the three cutters increases with cutting area under four set depths of cut (DOC). For different shape cutters, as shown in Figure 11(a) ~ 11(c), when cutting area is the same, the convex cutter has the largest axial cutting force, and concave cutter has the smallest values. The results show that when the three types of cutters bear the same axial force, the concave cutter has the deepest cutting depth and shows the strongest aggression, the DOC of flat cutter is the second, while the DOC of convex cutter is the shallowest. When the cutting depth is 4mm or above, as shown in Figure 11(d), the rock fracture occurs under the axial load rather than shear failure, thus presenting a different law of change.

(a) Sandstone, BA=10, DOC = 0.5mm (b) Sandstone, BA=10, DOC = 1 mm
Figure 11. Curves of normal force versus cutting area (Vosges sandstone, 10°).

Figure 12(a) ~ 12(d) show the results of Vosges sandstone, which is under 40MPa confining pressure, 120rpm rotary speed and 17.5° BA. Figure 12 show the same rule as Figure 11, that is, the axial cutting force of the three cutters also increases with cutting area, but the increase amplitude and change rule of the three curves are not the same. As shown in Figure 12(a) ~ 12(c), convex cutter shows an increasing trend of fluctuation. When the cutting area is 5mm², 15mm² and 30mm², the axial cutting force presents three small peaks, and then decreases and followed with increases. For concave cutter, the acceleration of axial cutting force increases firstly and then decreases, and then increases and decreases again, which is basically in accordance with the process of rock shearing and rock breaking, micro-crack expansion, debris breaking and rock shedding from the rock matrix. For flat cutter, axial cutting forces show a trend of reciprocating increase when the cutting area is small (2-6mm²), as shown in Figure 12(a). The main reason is that the cuttings were not cleaned in time during the experiment. However, the axial cutting forces show a distinct increase trend in a quadratic curve when the cutting area is large (7-34mm²), as shown in Figure 12(b) ~ 12(c).

Figure 11. Curves of normal force versus cutting area (Vosges sandstone, 10°).

Figure 12. Curves of normal force versus cutting area (Vosges sandstone, 17.5°).
Figure 13(a) ~ 13(d) show the results of Marcellus Shale, which is under 40MPa confining pressure, 120rpm rotary speed and 10° BA. When the cutting area is 2-6mm², the axial cutting force of convex cutter is the largest (3.15kN-12.83kN), and when the cutting area is 6-11mm², the axial cutting force of flat cutter is the largest (8.45kN-19.04kN), as shown in Figure 13(a) ~ 13(b). When DOC exceeds 1.5mm, the number of effective experimental data is limited due to micro-cracks in the rock samples, and the axial cutting force of concave cutter is the minimum (5.46kN-10.23kN), as shown in Figure 13(c) ~ 13(d).

Figure 14(a) ~ 14(d) show the results of Marcellus Shale, which is under 40MPa confining pressure, 120rpm rotary speed and 17.5° BA. As the cutting area increases, the axial force also increases, and the two show a linear relationship, as shown in Figure 14(a) ~ 14(c). Under the four cutting depths, the axial force of the flat cutter is the largest, followed by the convex cutter and the concave cutter. For this shale samples, under the four working conditions, concave cutter is the most aggressive, and flat cutter is the weakest.
Figure 14. Curves of normal force versus cutting area (Marcellus Shale, 17.5°).

Figure 15(a) ~ 15(d) show the relation curves between specific energy and the cutting area by Vosges sandstone. The cutting experiment is under 40MPa confining pressure, 120rpm rotary speed and 10° back angle (BA). For the three different cutters, the specific energy required by crushing per unit area rock fluctuates within their respective range, and the change range is not large. As shown in Figure 15(a) and 15(c), when the cutting depth is 0.5mm and 2mm, the specific energy of flat cutter required by crushing unit area rock is the largest, followed by the convex cutter and then concave cutter. In this case, the concave cutter has the highest cutting efficiency. When the cutting depth is 1mm, the specific energy of convex cutter required by crushing per unit area rock is the highest, followed by flat cutter and then concave cutter, as shown in Figure 15(b). When the cutting depth is 4mm, the crushing specific energy decreases with the increase of cutting area, which is mainly caused by the cracks in the rock.

Figure 16(a) ~ 16(d) show the results of Vosges Sandstone, which is under 40MPa confining pressure, 120rpm rotary speed and 17.5° BA. Among the three cutters, the specific energy of concave
cutter of crushing unit volume rock is the smallest, which are 39.7MPa-49.5MPa, 55.3MPa-55.8MPa, and 30.1MPa-38.3MPa, respectively. As shown in Figure 16(b) ~ 16(d). The specific energy of flat cutter and convex cutter is 1.2-1.5 times that of concave cutter. In Figure 16(a), the specific energy fluctuation of flat cutter is mainly caused by the failure of removing cuttings in time during the test. The energy required for breaking per unit rock of convex cutter is smaller than that of concave cutter, and thus, the cutting efficiency of convex cutter is higher than concave cutter.

![Figure 16. Curves of specific energy versus cutting area (Vosges sandstone, 17.5°).](image)

Figure 17(a) ~ 17(d) show the results of Marcellus Shale, which is under 40MPa confining pressure, 120rpm rotary speed and 10° BA. When the cutting depth is 0.5mm, 1mm, for Marcellus Shale, the specific energy required for crushing per unit rock increases with the increase of cutting area. In this case, the specific energy required for concave cutter cutting per unit rock is the smallest, as shown in Figure 17(a) ~ 17(b). When the cutting depth is 1.5mm, the energy required for convex cutter to cut per unit rock is the largest, while when the cutting depth is 1.75mm, the energy required for flat cutter to cut per unit rock is the largest, as shown in Figure 17(c) ~ 17(d).
Figure 17. Curves of specific energy versus cutting area (Marcellus Shale, 10°).

Figure 18(a) ~ 18(d) show the results of Marcellus Shale, which is under 40MPa confining pressure, 120rpm rotary speed and 17.5° BA. For flat cutter, when the cutting depth is 0.5mm and 1 mm, the energy required to break per unit rock remains basically unchanged, and the fluctuation range is within 5%, as shown in Figure 18(a) ~ 18(b). While in this case, the energy required by convex cutter and concave cutter to break per unit rock is increasing with the cutting area. Generally, the energy required by flat cutter is the largest and that of concave cutter is the smallest.

Figure 18. Curves of specific energy versus cutting area (Marcellus Shale, 17.5°).

6. Conclusions
PDC cutter is the key element to determine the cutting efficiency, work life and quality of PDC bit. In recent years, the improvement of PDC cutter material and cutter shape is the main direction of PDC bit innovation. Three typical cutters (flat cutter, convex cutter, concave cutter) are selected as the research objects in this paper. Based on the failure criteria of rock strength and the stress-strain law of rock...
during rock failure, the rock fracture process is analysed. The rock breaking efficiency of three cutters in Vosges Sandstone and Marcellus Shale is analysed through indoor single cutter experiments. The experimental results show that whether it is sandstone or shale, the axial cutting force, the cutting power and specific energy of concave cutter in per unit cutting area are the lowest when other parameters contain remain unchanged, indicating that the concave cutter is easier to invade formation and has the highest rock-breaking efficiency. When the cutting depth is small, the axial cutting force and cutting energy of convex cutter are higher than that of flat cutter when cutting per unit area rocks, means the cutting efficiency of convex cutter is relatively low at this time. For the condition of high cutting depth, convex cutter have higher aggression and cutting efficiency than flat cutter. For different lithology and different shape cutters, the rock breaking efficiency is not only affected by cutting depth, but also related to cutting back angle, rock cementation strength, and cuttings removal efficiency.

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