

How a Shaped PDC Cutter Forms the Cuttings to Improve the Cutting Efficiency

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Abstract

Improving drill bit efficiency is a golden goal for everyone. The drill bit performance can be controlled by two major parts: PDC cutters as driving elements and bit design to specify how the cutting elements would engage in the rock cutter interactions. The interactions between the rock and PDC cutter mainly depend on two steps: failing the rock and then removal of the failed rocks. Bits are designed to meet these expectations. Besides that, by considering the formations, a proper and target-focused design of a PDC cutter can be achieved along by shaping the cutters. A shaped PDC cutter is designed based on the learnings from the advanced modeling techniques on rock-cutter interactions. It is tested in many ways in lab and field trials for final modifications and evaluations. An important aspect of the effect of shaped cutters on the rock-cutting process has been studied based on the nature of the cuttings they create. A cutter's job is to fracture, break or shear the rock in soft or hard formations by creating ribbons, chunks, or powder-like cuttings. The shape of the built cuttings eventually could affect the drill bit efficiency. While the long ribbons or large chunks depict an efficient cut, the removal of the accumulated cuttings is another factor to consider and varies from brittle to highly ductile formations. In this short study, we focus on the shape and size of the collected cuttings/ribbons from single cutter tests on sandstone and evaluate how differently shaped cutters behave in the rock-cutting process.

Summary

Since the Polycrystalline Diamond Compact (PDC) was invented about half a century ago, PDC cutters and bits have experienced many great developments. PDC is now playing a key role in a multi-billion-dollar market that keeps the oil and gas drilling industry going forward faster and more durable in various applications from soft to very hard formations. The key to having a PDC cutter popular is to answer the demand for speedy drilling with a minimum of tear and wear (damage). One way to improve the rate of penetration (ROP) via the cutting element is to strengthen the cutter (materials), and the other one is to enhance the cutting efficiency by shaping the PDC. It is considered that using differently shaped cutters for various formations can provide superb performance compared to the baseline cutters (Rahmani, 2019). There are multiple reasons to

support this fact including (but not limited to) the specifically designed structure of the cutters (e.g., point loading concentration) that facilitates fracturing the rock, the higher impact resistivity design for very hard formations that allows a long-time crunching of the rock without dulling or the shape and size of the created cuttings that affect the bit balling chance and evacuation process.

Talking about the cuttings created by the PDC cutter, it should be mentioned that those accumulated ribbons or cuttings are generated due to the friction force in cutter-rock interactions and under confining pressure even as low as 150 psi (Rafatian, 2010). It is likely to happen when the interfacial friction angle between the face of the PDC cutter and the rock debris or cuttings is greater than the internal friction angle of the cuttings. It means during the process, the cuttings (ribbons) find less resistance path by sliding on each other rather than going up the face of the cutter (Rahmani, 2013). This is like scooping the butter sticks with a knife. It is worth noting that the strength of those accumulated cuttings under confining pressure is not lower than the rock strength itself (Ledgerwood, 2007).

There is a correlation between the cutting efficiency and the size or shape of the cuttings; usually, a long and large piece of cuttings refers to an efficient cut and lower MSE, simply removing a larger volume of the rock. On the other hand, smaller pieces of cuttings would reduce the chance of bit balling in highly ductile formations such as shales and likely easier cuttings evacuation in the drilling process.

Introduction

It has been indicated that besides the rock strength, there are other factors affecting the rate of penetration (ROP) including permeability, clay content, grain shape, size distribution, etc. In addition, it is believed that under pressure and temperature, the rock behavior alters from brittle to ductile (Rahmani, 2019). The range of pressure to initiate switching the rock mode varies, while for some rocks such as siltstone or limestone can occur under 15000 psi, almost double to triple pressure has been reported for Dolomite and Argillaceous sandstone (Jaeger et al., 2007). Failing the rock as a major goal to accomplish can start from initiating the first crack, expanding to the gross failure, and deforming the rock into the cuttings. Deforming the rock to gross failure consumes more energy than only initiating the

crack. Depending on the pressure, the cuttings can be created in the shape of rock chips (under atmospheric conditions), powder-like, accumulated cuttings, and ribbons-shape under pressure that can travel up the cutter's face. These ribbon-shaped cuttings could be smooth and flat on the side attaching to the cutter and tooth-shaped on the other side where the cuttings slide up over each other. Ledgerwood (2007) in his study stated that the energy needed to consume to deform plastically these already-created cuttings is much higher than the amount of energy required to fail the intact rock (Ledgerwood, 2007). These types of ribbons are not limited only to shale formations. They can be seen in other rock types such as Carthage marble and Indiana limestone in Rafatian's work (2010) and Torrey buff sandstone in Rahmani's work (2019). In the earlier one, they concluded that the accumulation of the cuttings due to friction is the reason for to drop in ROP (Rafatian 2010). The same phenomena were observed in single cutter testing in the NOV facility. Both in Ramani's work in the past years and in the current study, similarly, ribbons were formed in front of the PDC cutter while it was cutting Torrey buff sandstone samples under confining pressure and in presence of mineral oil as the fluid with a constant RPM and fixed DOC. The capability of video capturing during the test process is beneficial to watch the rock-cutter interactions in real-time.

Experiments and Observations

A total of three PDC cutters were selected for this study, i.e., cutters #1, #2, and #3. No. 1 is the baseline cutter, and the other two cutters are representing the shaped cutters. No. 2 has a V-shape geometry and much lower surface friction than the baseline. No. 3 is a non-planar cutter with a point load concentration and two friction surfaces on the face and flanks. Tests were done on Torrey buff sandstone under 3000 psi at the constant depth of cut (mainly at 2 mm/rev) when the drilling fluid was mineral oil. Every cutter rotates for one full revolution at 60 rpm. At the end of the tests, the cuttings and ribbons were collected, and the sizes and shapes were measured and recorded. A few tests on other DOCs were conducted too.



Figure 1 – PDC cutters used in this study.

It is worth mentioning that the cutters were selected not to compare their efficiency but to study the quality of the cuttings they create. Otherwise, for a comparison study on cutter efficiency, the first rule to follow is to compare apple to apple and provide all the similar conditions except one factor to compare. However, in this study, more than one factor may be prone to change from one cutter to another. The cutter on the left is round with a rough surface (baseline). The cutter in the middle is a V-shape with a super fine surface and finally, the cutter on the right is round but with two surface roughness way

far from each other.

The pictures below depict how the created ribbons are traveling up on the cutter's face of different shapes or surface frictions (friction coefficients). They are all taken at the same level of penetration. Picture 1 shows a planar cutter with a non-smooth (coarse) cutter face where small ribbon-shaped cuttings are created and got packed in front of it. In picture 2, a planar but V-shaped cutter is cutting the rock by fracturing and the long ribbons extrude up along its super smooth cutter face. The thickness of ribbons represents the depth of cut which is 2 mm/revolution in this series, for lower or higher depths of cuts they would change. In 3rd picture, a non-planar cutter with a plow-shaped smooth tip fails the rock. The smoothness of the cutter's face is a mixture of those high and low frictions of other cutters. This time instead of having thick and long ribbons as wide as the cutter diameter, the ribbons become smaller and split into a couple of flows. One channel goes up along the mirrored cutting tip and curls forward due to the relieved surface at top of the cutter and two other flows split to the sides due to the angled flanks of the cutter. This can be recognized as an effect of a shaped cutter that can be designed for specific formations to reduce the cutting forces due to the point load concentration and lower the chance of cuttings accumulation in front of the cutter.

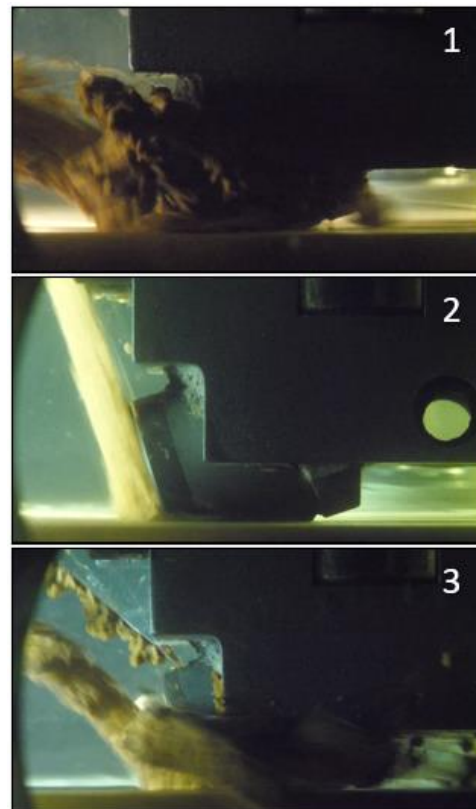


Figure 2 – Real-time observation of rock-cutter interactions for different cutters while cutting Torrey buff sandstone.

Results and Interpretations

Tests were performed in the NOV testing facility in Conroe, TX, employing the single cutter lab testing apparatus. The machine's capability is to measure tri-directional forces for a cutter in the rock-cutting process and to capture the video through the sapphire window on the pressure vessel while the cutter is cutting the rock and creating ribbons. The forces are measured and compared for all three cutters for a portion of the revolution that the cutters were cutting at the same and fixed depth of cut as 2 mm. Cuttings forces on a single PDC cutter are axial (normal), tangential (drag) and radial as illustrated below.

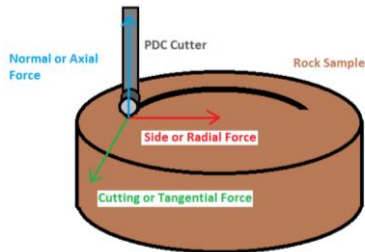


Figure 3 – Decomposition of the forces on a single cutter.

Two sets of tests ran on a 7" Torrey buff sandstone rock sample. First, the cutter rotates one revolution on an intact surface. Then, after collecting the cuttings, the next shot would cut the same but pre-grooved path which surely more volume of rock can be removed. Therefore, two cuts with different cut shapes create different sizes/shapes of ribbons.

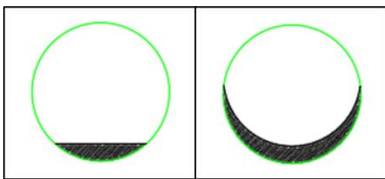


Figure 4 – Illustration of the cut shapes created by a round cutter in two shots: intact rock (left) and pre-grooved rock (right)

It is seen that some of the ribbons are curved to one side while the cut shape looks to be symmetric. That is due to the slightly asymmetric force on one side of the ribbons because of the relatively small circular path of the cutter compared to the path radius. In fact, in this small path, the radius from the center to one edge is a bit smaller than the other edge and that would cause a higher drag force to the center and curling of the ribbons. This phenomenon grows by increasing the cut shape as it is seen per the pre-grooved ribbons created. The effect of ribbons curling toward the center of the cutting path (or bit) was seen before in a study on cutters arrangements on bit by the author (2019). It was seen that this curling would affect the lateral forces a bit and differentiate between the spiral and reverse spiral arrangements of cutters on a bit. (Sheikhrezaei, 2019)



Figure 5 – Cuttings from intact rock (left) and pre-grooved rock (right).

By measuring the dimensions of the ribbons, the thickness was found to be clearly relevant to the depth of the cut. For most cases, this thickness is about 2.5-3 mm which is close enough to DOC; it should be noted a portion of this thickness is due to the edges of the ribbons that are pushed up and compacted. For the first group, the width of the ribbons for cutters #1 & #3 are close and around 5 mm while for cutter #2 that is about 8 to 10 mm, showing that on a well-smooth surface, the cuttings can be easily generated and advanced up the face. The longest ribbons belong to cutter #2 which may reach up to 50 mm, almost double the other two cutters. In the second group, the width for cutters #1 & #3 are again similar and around 7 to 9 mm, while the range for cutter #2 is between 6 to 11 mm. The length of the ribbons may be less than 30 mm for those cutters while for the smoother cutter, it can be extended to 57 mm. This shows the benefit of a super fine and minimal fractioned surface for a shaped cutter (#2) which makes the cut to be highly efficient.

It is figured out that the thickness and width of the cuttings depend on the depth of the cut. While it is thicker and wider for high DOC, the tiny and thin ribbons were collected for lower DOCs which align with lower cutting forces. The width for the collected cuttings by a round mirrored PDC cutter is increasing from 5 mm to 10 mm for 0.5 mm DOC to 2 mm DOC. The thickness as well increased from about 1.8 mm to 2.7 mm for those depths of cuts.

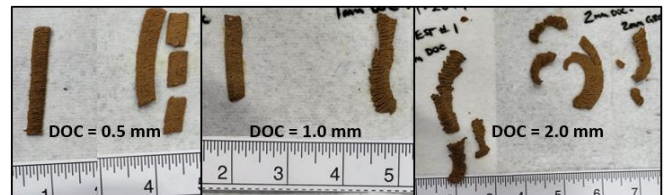


Figure 6 – cuttings collected for a round smooth-face PDC cutter at different depths of cuts. In each box, the left group of ribbons is for the intact rock and the right group of ribbons is for the pre-grooved rock.

For instance, the axial forces for this round cutter correlated to these three depths of cuts are presented below.

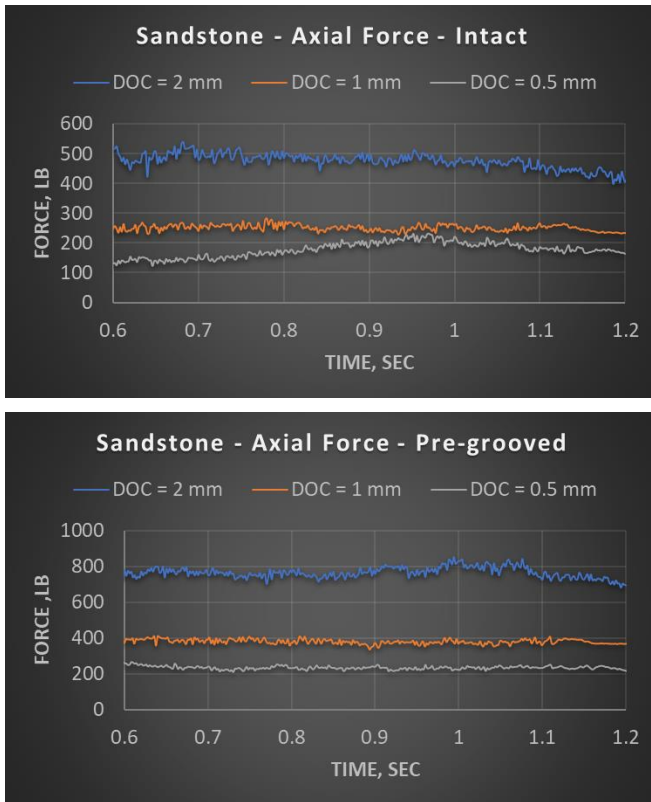


Figure 7 – Axial forces for a mirrored round PDC cutter which is cutting at different depths of cuts.

Comparing the back of the cuttings tells us that there are two types of cuttings. For the cutters with very smooth cutter faces (#2), the underneath of the cuttings is flat and polished and clarifies how/why the ribbons can go up the face easily. While for the other group (#1), the coarse and rough side at the bottom of the ribbons would increase the energy consumed to build up the ribbons over the face due to higher friction.

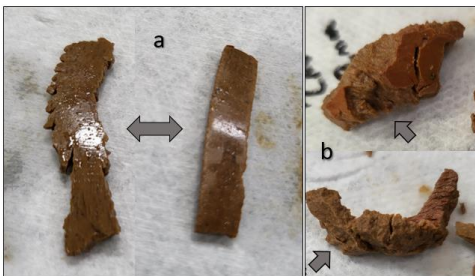


Figure 8 – back of cuttings; super smooth cutter (a) vs. baseline cutter (b)

By correlating the force graphs and the ribbons’ dimensions, one can interpret that for this sandstone formation the longer the ribbons created, the lower the forces recorded. That is true when there is no concern about occurring bit balling. In addition, a lower interfacial friction angle, i.e., a smoother cutter surface

strongly reduced the cutting forces on the cutter since the large pieces of cuttings are easily created and can go up the face. It is seen that for soft formations such as Torrey buff, the effect of having a polished face cutter crucially reduces the forces. However, in harder formations, having a sharper cutting edge to fracture the rock becomes a strength and value.

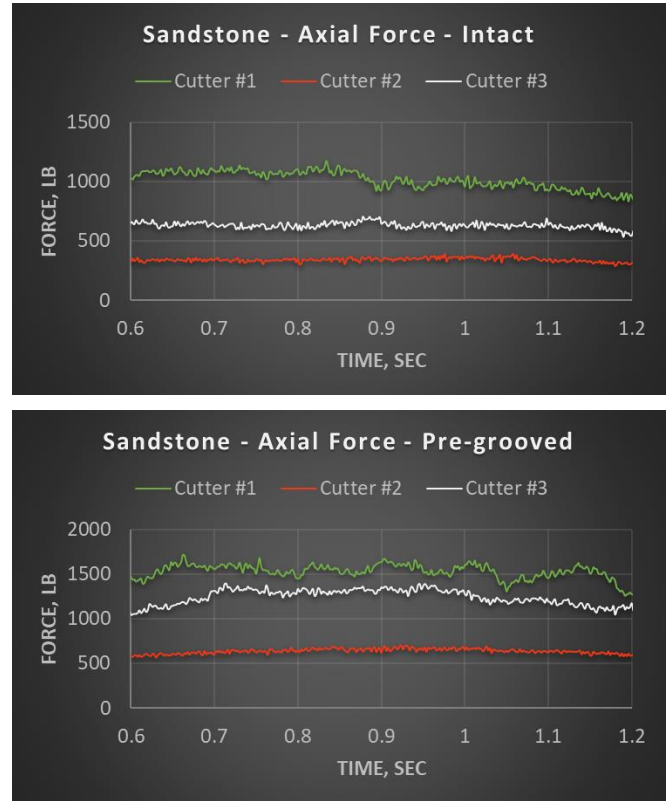


Figure 9 – Force Graphs: intact rock and pre-grooved rock. (Cutter #1 is the round baseline, #2 is the mirrored V-shaped and #3 is the round non-planar point load concentrating cutter.)

One other interesting point to study could be the effect of fractures created by the previous cut or cutter on the new revolution. However, that needs the same cutting area to study. In our case due to the different cut shapes, the impact of the microscopic fractures generated by the cutter on the first round of testing cannot be isolated and studied. These types of fractures created by a PDC cutter have been studied by the author (2019) via CT scanning of the sample after a cut. The results showed that depending on the rock and cutter’s shape and size, the cutters can leave micro-fractures on the grooves that will facilitate the next revolution of rock removal by cutter.



Figure 10 – Illustration of the possible existence of fractures left on the grooves that may reduce the cutting forces for the next round of cutting; studied by the author in 2019.

Conclusion

Ribbons-shape cuttings can be created in front of a PDC cutter while it is cutting and drilling under confining pressure into a ductile formation such as shale or soft sandstone. For an efficient cut, it is preferred to have long and large ribbons or rock pieces and chunks (which represent the removal of a larger volume of rock), while for better cuttings evacuations and bit balling avoidance, the smaller cuttings might be considered as well. Regardless of the formations or bit design, a PDC cutter can play a key role in creating and shaping the cuttings in front of the cutter. It is seen that a shaped PDC cutter can increase the cutting efficiency and at the same time form the cuttings into a smaller size in the soft formation. In addition, it is seen that with a polished V-shaped cutter face, efficient cutting by generating greater ribbons was achieved which strongly increased the efficiency. In this short study, three PDC cutters were tested, and based on the force graphs and ribbons' shape/size the cutting efficiency was investigated. The benefit of a shaped cutter over the baseline cutters is reported.

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