

# Overcoming Shock Loads to Improve Drilling Efficiencies: Case studies of bit and cutter designs that drilled Chert Interbedded Lithologies and Dense Conglomerates

Prabhakaran Centala, Peter Wu, Moustafa Saleh, NOV Inc.

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## Abstract

This paper outlines the success of bit design with new generation cutters that enable drilling in hard nodular chert interbedded lithologies while maintaining cutting structure integrity, which currently poses challenges to fixed cutter bits.

Impact test results revealed that the optimized multi-faceted cutter showed clear dominance over conventional cutters. Observations from drill bit tests suggested the sensitivity of these cutter placements on sections of the bit profile, which will affect rate of penetration (ROP) effectiveness. The first field test bit results correlated with this shortcoming. This was a very critical validation which led to bit design guidelines for future designs. Subsequent field tests were with bit designs that adhered to the bit design guidelines for such cutters.

A 6-1/2" test bit incorporating the multi-faceted cutter wasted in a horizontal section consisting of sandy conglomerates; wherein previous bit runs with planar cutters reported low footage and ROP. The result was 27% longer footage than the top 10 best offsets average.

An 8-1/2" size bit was run in a lateral section drilling shale, nodular chert and interbedded limestone where both conventional PDC and "roller cone+PDC hybrid" bits have been run with short intervals. The test bit with multi-faceted cutter resulted in a one-run interval, drilling the entire 368 m with the fastest ROP. The details of laboratory and field runs are discussed in this paper to explain the science of multi-faceted cutter benefits.

## Introduction

Fixed cutter bits have made significant strides in drilling hard rock formations. Typically, low depth of cuts has been adopted while drilling so as to not exceed the polycrystalline diamond cutter (PCD) strength limits and to avoid premature failures. This results in low ROP and small cuttings. Attempts have been made by various bit designs to improve the cutting's size and

thus ROP (Sebastian, et.al, 2008). The drill bit industry has witnessed often what is then conceived as promising bit technology (Placido, 2004) run a short life due to various shortcomings as compared to what roller cones have been able to consistently deliver despite lower ROP. However, the fixed cutter bit community has continually and incrementally pushed the boundaries of the bit designs and PCD technologies in drilling hard rock lithologies to explore promising reservoirs. Understanding the limitations of fixed cutters bits, various drilling practices have been explored to bring about improved drilling efficiencies (Graham, et.al 2003).

Generally, while drilling hard quartzite rock formations fixed cutter bits demonstrate good drilling efficiency in the early stage of the drilling. What is observed is that the ROP can fall rapidly, and the working life of the bit is shortened. This is primarily due to premature wear damage to the PCD compacts. These quartz particles help accelerate above normal abrasion wear and erosion on the working surfaces/edges of the PCD compacts. In addition, due to low depth of cuts, the PCD surface temperatures can rise and cause thermal degradation in the diamond layers. One approach to avoid abrasive wear and thermal degradation is to apply higher weight on bit to fracture the rocks aggressively. The consequence is that the cutters will be subjected to much higher axial and tangential loads and can lead to severe impact damage (Bin, et.al, 2020). Another rising concern in drilling hard rocks formations is the phenomenon of HFTO. There is fair amount of ongoing research towards mitigating the HFTO through drilling tools development and bit design methodologies. It has been observed that limited depth of cut by the cutters is a considerable factor to induce HFTO (Rob et.al, 2021)

## Forces on PCD Cutters in Interbedded and Chert drilling

PCD cutters along the blades of a drill bit are subjected to a variety of mechanical loads. Mechanical loads refer to the

forces that are applied to the drill bit cutters as they cut through the rock formations. Because of weight on bit and bit rpm, the cutters penetrate the rock formations and shear the rock away continuously, generating desired rate of penetration. The rock crushing force acts equally back on the cutter tip/edge/area. The magnitude of forces is dependent on the depth of cut and rock formation strength. These vertical rock fracturing forces become very significant in magnitude while drilling hard formations. These vertical fracturing forces are typically benign when drilling low strength formations. While drilling a transitional zone of interbedded formations, the cutters encounter both low and high strength rocks in short time intervals. The drill bit moves with high ROP in low strength formations then suddenly encounters hard rock due to interbedded lithologies; the bit cannot penetrate easily. In such situations, the cutters get subjected to fluctuations in the rock fracturing force magnitudes. These fluctuations when occur in very short time intervals can result as mechanical impact loads. Such impact loads can exceed the fracture toughness of the cutter, resulting in premature broken cutters and compromising the bit cutting structure integrity.

Another mechanical force on the cutter in the process of drilling rock formations is the tangential force also known as shear force or drag force. The drag forces from all cutters on bit contribute to bit torque. In homogeneous drilling applications, these drag forces can typically be steady. Again, the magnitude of the tangential force on the cutters depends on the cut shapes and rock strength. Hard rock drilling will apply higher shear forces on the cutter. While drilling nodular chert lithologies or chert segments, the failure of such rocks occurs intermittently as opposed to the continuous shear such as in homogenous formations.

As a result, the cutters can be subjected to lateral impact loads and lead to premature failure of the cutters and subsequently reduced drilling efficiencies.

Overall, the loads encountered by drill bit cutters while drilling chert and conglomerate formations can be highly variable and challenging. Drill bit community has been developing PCD cutter grades that have high wear resistance and thermal threshold levels. In addition to these properties, there is a need to explore the use of specialized drill bit designs with shaped cutter technologies to minimize and prevent premature cutter failures so that challenging rock formations can be drilled effectively and efficiently.

### Advancement in Cutter technology

Standard cylindrical shaped cutters have been in use since the advent of fixed cutter bits. Various diameters have been developed and the industry has standardized a handful of diameters into their bit design practices. To date, a combination of different diameters along with back rake and side rake combinations are being iterated for different applications and have continuously brought about effective drilling solutions. As we experience each win, the operating parameters threshold

gets pushed further in terms of weight on bit and rpm.

These cylindrical cutters have always maintained a flat profile or in other words, a single planar surface on the top of the PCD layer that interacts with the rock formation. The cutter's toughness and strength property were always a derivative of the PCD material's sintered microstructural contents and granular anatomy.

In the recent past, due to the advent of manufacturing technologies for machining PCD cutters, there is a shift towards shaped cutter technology. The PCD cutters by far are still cylindrical, but the top PCD surface is no longer planar or flat in profile. A myriad of iterations is being explored. The industry prefers to term such cutters as non-planar as they tend to deviate from the flat surface into non-flat surface. These non-flat surfaces can be a combination of several flat facets to form of pyramid in one extreme to a complex geometrically non-planar surface. The design variants are intended to bring about improved drilling efficiency. Shaped cutter approach was leveraged primarily to enhance rock damage and increase rate of penetration. However, while drilling hard rock and interbedded lithologies, the forces required by the cutters are still significant and can exceed the strength properties from a standard round cutter. Cutter chamfers have been iterated to help overcome impact loads.

### Multi-faceted 5DX Shaped Cutter

Figure 1 illustrates a shaped cutter which consists of multi-faceted geometry in lieu of a flat surface of the cutter. Each of the facet has a functional intent while interacting with the rock formations. There are three major facets that interact with the formation as the bit is drilling. The angles of each facet have been engineered such that the working region of the cutter has a much tougher mechanical property as compared to round and flat faced conventional PCD compacts.

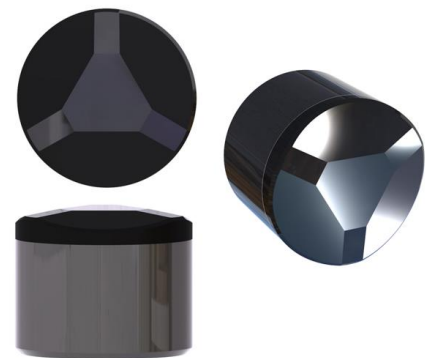


Figure 1: A Multi-faceted 5DX shaped cutter.

Engineering analysis demonstrates that this shaped cutter can be subjected to higher loads before experiencing premature failures in the event of impact loads both in axial and tangential directions. The primary facet geometry which is a rectangular profile at a 3D plane provides a mechanical design advantage.

When higher WOB are applied to the drill bit to crush the formation the cutters are bound to encounter with higher reactive forces on to them. Such a design enables the cutter to withstand higher loads. The secondary facets geometry are inclined to the primary facet. The slopes are in three-dimensional space and are optimized to enhance the impact resistance of the cutter space of interaction with the formation. Figure 2 illustrates an instance of an engineering analysis wherein a multi-faceted cutter is compared to a round single plane faced cutter of equal diameters and chamfers. The analysis shows that the multi-faceted cutter can impart higher stress to the formation for the same depth of penetration. The science of geometry in the mechanical design world is not revolutionary, but to the cutter technology is revealing. Combined with the advancements in manufacturing capabilities opens a new domain to shaped cutters and in this case a cutter that can be employed to provide drill bits to higher sustainability while drilling hard rock formations.

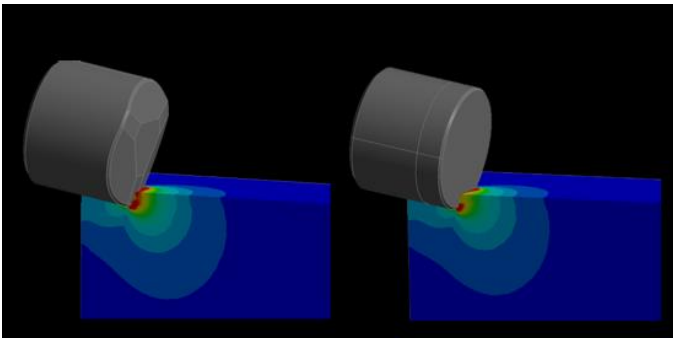


Figure 2: 5DX Multi-faceted shaped cutter

Laboratory tests were undertaken at the cutter level and bit levels to validate the engineering analysis about the multi-faceted cutter discussed in this paper. An impact test was conducted on the cutters to evaluate and compare the toughness between the multi-faceted shaped cutter to that of the round flat single plane cutter. Since the testing was about comparing the shape of the cutters, two different diamond cutter material grades were chosen for this testing. This will allow us to understand and normalize data solely due to the science of geometry to PCD cutters. Figure 3 summarizes laboratory observations. It was very evident that the multi-faceted shaped cutter could withstand higher impact loads. The laboratory data suggest that these shaped cutters can withstand 60-70 percent higher impact loads as compared to standard round cutters. The plot in Figure 3 shows two grades of cutters namely grade A and grade B. Due to microstructure design, Grade A cutter diamond material provides a higher impact resistance as compared to grade B diamond material when cutters of same planar geometry and dimension are tested. In grade A the multi-faceted shaped cutter in Figure 1 demonstrated an average of 60 percent increase in impact strength. In grade B the multi-faceted shaped cutter demonstrated an average of 70 percent increase in impact strength. The series of impact strength tests clearly showed what the science of shaped of cutter technology has to offer. A series of other bit related experiments were conducted

in the Laboratory to evaluate the durability of these multi-faceted shaped cutter as compared to round single plane-faced cutters. Through the experiments it was ascertained that these shaped cutters could tolerate impact loads much better than the round single plane faced cutters. It was observed that the round cutters would experience failures while the shaped cutters would be effective without any failures.

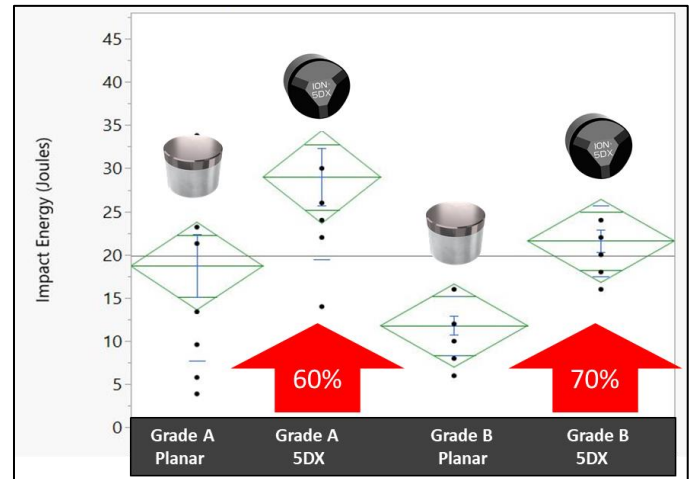


Figure 3: Multi-faceted shaped cutter impact resistance is Superior: compared to round single plane faced cutter

Another series of tests was conducted in the laboratory, regarding the placements of the multi-faceted shaped cutters along the bit profile. The purpose of the test was to identify optimum arrangements of the multi-faceted shaped cutters. Through design of experiments the multi-faceted shaped cutters were placed in different arrangements as shown in figure 4.



Figure 4: Illustration of some cutter layout practices tested in the Laboratory

**Field Run Case Studies**

**Case Study 1: Field test run in a sandy conglomerate**

Mahu Oilfield is known for its thin conglomeratic pay zone. This oilfield has long horizontal displacements with an average of 1800m and has a lithology consisting of mostly sandy conglomerates, interbedded with layers of claystone.

Figure 5 depicts a typical well plan for the Mahu oilfield. Pay zone  $T_1b_1^1$  is where the fixed cutter drill bits encounter sandy conglomerates with layers of claystone interbedded. Also, the pay zone thickness is less than 3m which attributes to the difficulties of direction control. Rotary Steerable System (RSS) would be ideal for better trajectory control, however bent housing motors were picked up for inclination control as fracturing operations in the field would increase the downhole risk.

Drilling such interfacial severity resulted with significant cutter damage and ending with short footage drilled. Multiple runs were needed to finish the whole horizontal section with an average footage of less than 400m. Such interfacial severity applications are getting more challenging as the PDC bit cutters must withstand intermittent shock loads both: axial and tangential. In addition, the eccentric rotation drilling mode used along with bent housing motor would intensify the shock loads on the cutters.

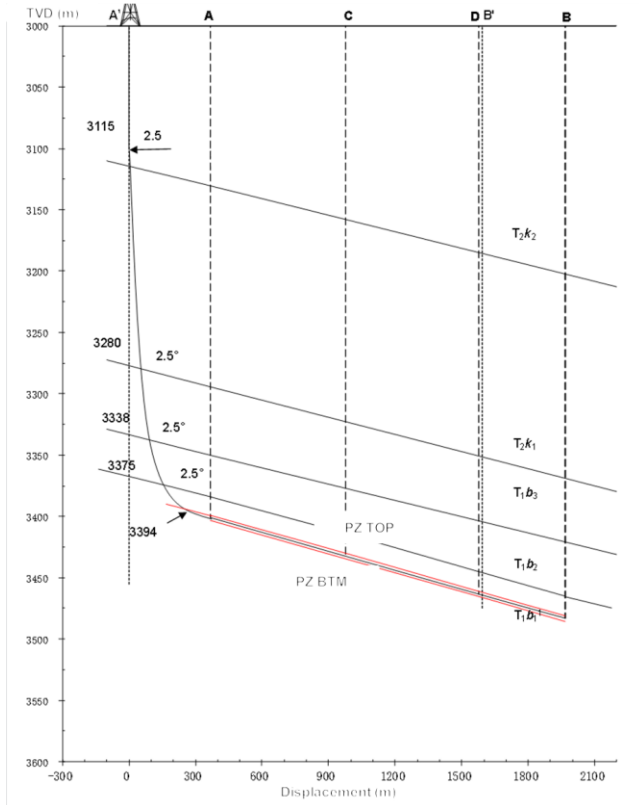


Figure 5 – Typical Well Trajectory for Mahu Oilfield

Figure 6 illustrates a 6-1/2” diameter fixed cutter bit with 6 blades that was designed using 13mm cutters. The cutters used in the primary placement were the multi-faceted shaped cutters shown in Figure 1.

As a first field test and for comparative study, the shaped cutters were situated in the outer region, also termed the cone and shoulder regions of the bit profile. Standard round cutters were placed in the inner or nose region of the bit profile. Both the round and shaped cutters were of the same impact grade. As understood for laboratory test studies alternate placement of multi-faceted cutters on outer (cone and shoulder) region was adopted. The intention was to enhance the outer durability of the cutting structure on bent motor application.

The test bit was placed on a 1.25° bent housing motor in the subject well. The footage goal set for this bit was to be a minimum of 500m.

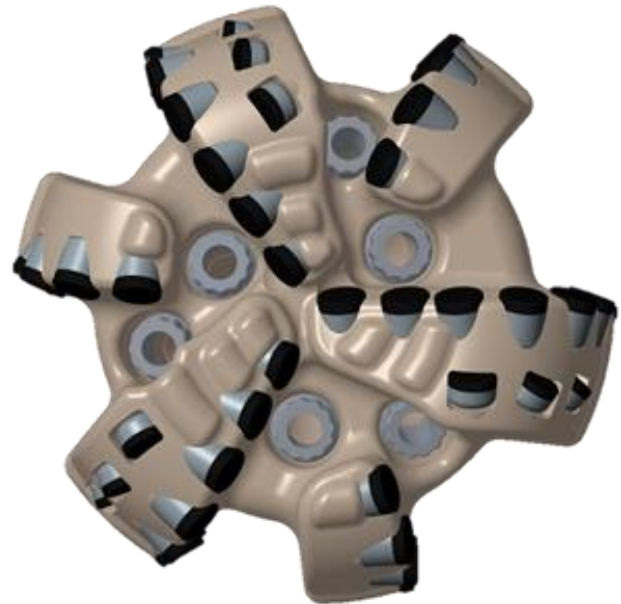


Figure 6 – Multi-faceted Cutters Placement

During the whole run, frequent inclination and azimuth corrections were made by directional driller due to very thin layer of pay zone. It was reported to have good rotary and sliding ROP in sandy conglomerates.

This fixed cutter test bit with multi-faceted shaped cutters finally drilled from MD 3645.84m to MD 4552.04m, total footage of 906.2m in 196.1 drilling hours, with an average ROP of 4.62m/h. Reported data was it drilled 9% longer than the previous record, and 27% longer than the top 10 best offsets average. Figure 7 provides the comparison data. Bit A is the bit design with the multi-faceted shaped cutters.

Also, reported was that the test bit was pulled out of hole for

motor hours. The bit dull revealed the following: All inner region cutters in the nose region had failed and cored out. All multifaceted shaped cutters in the outer region were still effective. This went out to show that these shaped cutters could withstand the impact loads and drill interfacial severity. Due to the durability of multi-faceted cutter, especially impact resistance the bit life and footage was extended despite the cored out inner. The next test bit planned will have the multi-faceted cutter in the inner region too. Figure 8 shows the test bit with multi-faceted shaped cutters help maintain the cutting structure integrity and achieve the record footage.

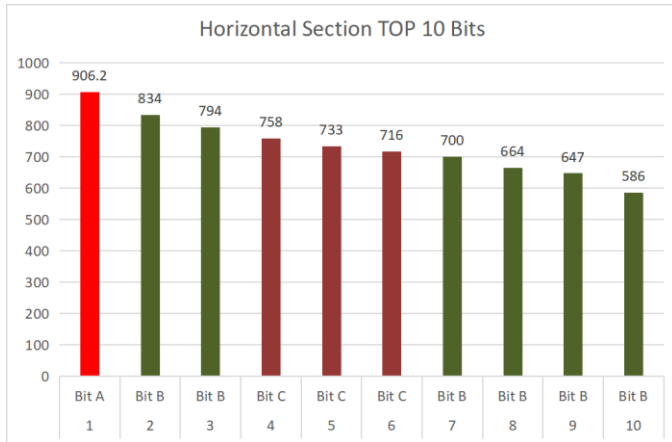


Figure 7 – Top 10 Best Footage Performance Bits



Figure 8 – Dull Photo of Bit with Multi-faceted Cutters

### Case Study 2: Field test run in a lateral section with shale and interbedded limestone/fossil streaks

The Wujiaping formation is a sedimentary rock formation in China. It is part of the lower Permian system and is composed of interbedded sandstone, siltstone, mudstone, hard limestone containing fossil streaks and coal. The Wujiaping formation is an important source rock for coal-bed methane (CBM) production in China. The complexity of the highly interbedded formation can impact the overall drilling efficiency.

The shale gas project in Hongye block is intended to explore the shale gas in the lateral section of Wujiaping formation which has the hard limestone/fossil streaks within the shale. Fix cutter bits and hybrid bits (roller cone + fix cutter) had been run with short intervals (98m average) and low ROP (5.36m/h average) resulting in very low cutting efficiency and high drilling cost. Different bit designs both fixed cutter and hybrid designs have been tested in the Wujiaping formation.

Premature cutter damage in outer areas was commonly observed on all the above tested bits and attributed as the primary reason that caused low performance. The nature of the interbedded formation subjected the cutters to frequent impact loads alongside abrasion wear on shoulder region of the bits as can be seen on various tested bits shown in Figure 9A-D.

Figure 10 illustrates a 8-1/2” diameter fixed cutter bit with 6 blades, that was designed using 13mm cutters. Both shaped and standard cutters were used on this bit design. The multi-faceted shaped cutters were placed both in the inner and outer regions of the blade. In addition, the shaped cutters were arranged in a lab evaluated design, which alternates with standard round cutters as illustrated in the figure. Again, this was repeated based on the success observed from Case Study 1: to enhance the outer durability of the cutting structure on PDM applications, while maintain the drilling efficiency

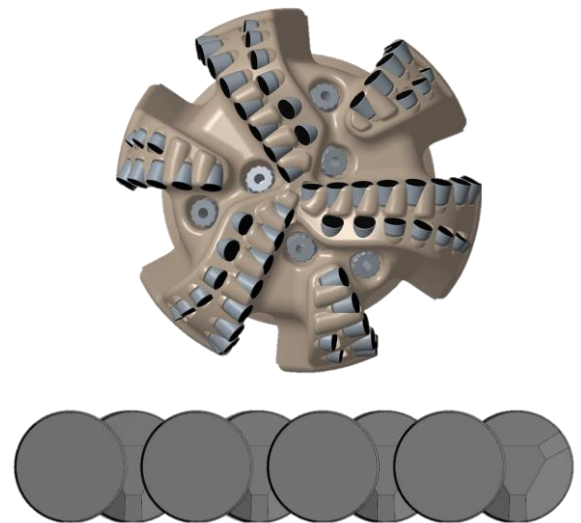


Figure 10– Bit design for Wujiaping formation with multi-faceted shaped cutter placement on bit blades

This fixed cutter test bit (Bit A) with multi-faceted shaped cutters drilled from MD 6122 m to MD 6490 m, total footage of 368m in 42.49 drilling hours resulting with an average ROP of 8.66 m/h. Both footage and ROP are much higher than the offset bits as shown in Figures 11 A & B. This achieved the longest interval compared to competitors' bits in the same well. The reported dull grading was 1-2-CT-N/S-X-I-WT-PR. Figure 11A shows a comparison of Bit A with offset fixed cutter bit designs. Figure 11B shows the Bit A comparison with hybrid bit design.

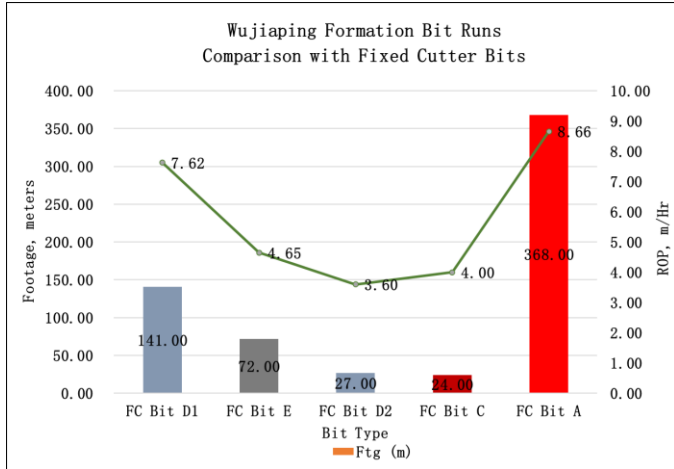


Figure 11A: Fixed cutter bit design performance comparison Bit A is bit using multi-faceted shaped cutters

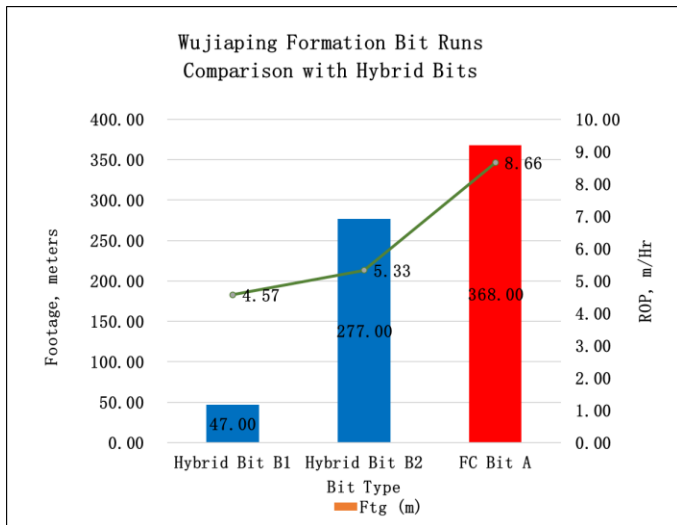


Figure 11B– Hybrid bit design vs Fixed cutter bit design Bit A is bit using multi-faceted shaped cutter

Both cases demonstrate the science of this shaped cutter: how the multi-faceted shaped cutter could effectively withstand shock loads and maintain its cutting edge during the whole run while drilling hard rock and interbedded formations.

### Drilling In West Texas

This section of the paper discusses the challenges fixed cutter bits encounter in drilling the Brushy Canyon and Avalon formations within the southern Delaware Basin. These formations are primarily composed of limestone, siltstone, and sandstone. It also contains some shale, chert and hard calcite stringers interbedded within short depth intervals.

Figure 12 shows a layout of the formations that a fixed cutter drill bit will need to encounter. Also shown in the figure is a typical MSE plot adjacent to the formations. It can be noticed that the MSE peaks up significantly and with severe fluctuations in magnitudes. This is an indication of high level of interfacial severity the within the interbedded formations. The nature of the interfacial severity varies from the southern to northern end of the Delaware basin, with laminar calcite streaks dominating in the south and nodular chert inclusions occurring in some areas of the north.

Approximate TVD Interval	Formation Name	Description	Bit MSE (0 -150 ksi)
6000' -7000'	Cherry Canyon	Sandstone/limestone/Shale	
7000' - 8000'	Brushy Canyon	Sandstone/ Shale with Hard Calcite Stringers	
8000' - 8400'	Bone Spring Limestone	Interbedded limestone stringers	
8400' - 8800'	Avalon	Sandstone/ Shale with Hard Stringers	
8800' - 9600'	Bone Spring Sands	Interbedded sandstone with hard limestone streaks	

Figure 12: Layout of Brushy Canyon and Avalon with Bit MSE

Like drilling any interfacial severity applications, good bit designs and good drilling practices must be adopted. Bit design and cutter selection is critical to avoid premature failures due to impact loads both in axial and tangential directions and help extend the footage drilled.

The section of Brushy Canyon, Bone Spring, Avalon and Bone spring sand formations account for about 1800ft in total depth. On either side of Bone Spring Formation consist mainly of Limestone and Sandstone and are notorious for extremely hard Sandstone streaks. But the interfacial severity damaged encountered by the drill bits makes the footage drilled short and

the need for multiple bits and; thus proving costly. It would be ideal to reduce trip times through reduced number of bits needed.

Also, in southern ward county in Delaware basin the field has a lot of chert nodules interbedded in high compressive strength limestone, which is a major challenge for fixed cutter drill bits. The cutters will need to endure the high frequency of tangential loads.



Figure 13: Typical bit dull in drilling

Figure 13 is a typical dull from a run in these applications. This bit was run on conventional BHA to drill the intermediate section in Delaware Basin Ward County. The bit drilled from 5244 ft to 8566ft a total footage of 3322 in 52 drilling hours with average ROP 76.1 ft/hr. The bit pulled out for penetration rate at top of Avalon formation in ring out condition at the nose area with severe breakage on the inner cutting structure due to high axial load.

Bits forensics suggest bits are damaged mainly in the lower Cherry Canyon and Avalon with the presence of Chert, depending on local lithology. In other areas of the Delaware basin this may also be observed in hard sandstone streaks in the Bone Springs. The damage severity results on the cutter due to being overloaded with torque acting directly into the cutter's face. The cutter will also have a high axial load from WOB, so the failure is from combined loading.

A comprehensive approach to managing performance is required for the intermediate sections and tougher cutters required to withstand tangential overload in the transition out of the calcite stringers and hard sandstone streaks.

Thus, this is an application where a multi-faceted shaped cutter

shown in Figure 1 would be appropriate. An appropriate bit design with ideal multi-faceted shaped cutter placements could yield successful runs and reduce drilling cost by extended footage and trips cost with fewer bits.

### **Case Study 3: Pilot test run in Delaware basin**

A 8.75" seven bladed fix cutter bit fitted with 16mm multi-faceted shaped cutters in the primary location was lowered together with a bent housing motor in the subject well in southern Ward County in Delaware Basin. This field has a lot of chert nodules interbedded in high compressive strength limestone, which is challenging for any fixed cutter bits.

This application, typically known for its interfacial severity challenges where 80% of the bits do not drill more 3,500 ft before being pulled for PR and most of the bits show damage on the inner sections of the bit.

The test bit built a 9-degree tangent interval and dropped back to 2 deg at the end of the run. The bit drilled from 5140 ft to 9123 ft, a total footage of 3983 ft in 39.5 drilling hours with an average ROP of 100.8 ft/hr.

Bit was pulled out of hole for down hole tool failure, the bit came with the lowest inner dull & outer dull rating and drilled further and faster than the offset bit runs. Most of the multi-faceted cutters were intact with lesser wear flats and minimal spalling compared to standard cylinder cutters. Statistics suggested that this bit drilled 30% longer interval and 13% faster ROP comparing to the offset wells.

It is apparent that the multi-faceted shaped cutter withstood shock loads better than the standard top planar cutter while drilling interbedded and nodular lithologies. Premature failures such as diamond table delamination under high shocks were eliminated. Due to the aggressive rock fracturing capability, it reduced the low depth of cut rock removal method and hence avoided any onset of thermal degradation symptoms and minimizing other failures process such as spalling.

Figure 14A and 14B shows a comparison between two bit dulls on the same application and BHA configuration. Bit A was fitted with multi-faceted shaped cutters in a proprietary arrangement. Bit B was fitted with standard round cutters with planar top surface. Both cutters were of the same grade. On the same location of the cutting structure, the multi-faceted cutters have better dull condition than the conventional cutters. Clearly evident that the bit design with shaped cutter technology can manage and drill interfacial severity better. From the figures 14A & 14B, it is very evident that the multi-faceted shaped cutters survive the high impact loads both axial and tangential while none of the standard flat faced round cutters could survive and resulted in severe damage. This was observed in all the blades of the bit dull.



Figure 14A: Test Bit A Dull fitted with multi-faceted shaped cutters



Figure 14B: Test Bit B Dull fitted with standard planar faced cutters

### Conclusions

Since their inception and successful applications in fixed cutter drill bits, PCD cutters have been only cylindrical in shape and with a single planar face which interacts with the rock formations. These PCD cutters have come a long way in the mechanical properties through the technologies of grain structure optimization along with high-pressure and high-temperature processing algorithms. Combined with evolving bit designs, fixed cutter bits have successfully been drilling hard

rock formations which were previously only considered drillable by roller cone bits.

In the recent years, there has been more research and development towards shaping the diamond top surfaces into three dimensional in lieu of the planar shaped cylindrical cutters. In addition to the cutter grades improvements, shaped cutter technology is enabling to push boundaries in drilling hard rock formations.

The multi-faceted shaped cutter discussed in this paper has demonstrated in various field runs that it can withstand impact loads while drilling hard rock, chert, and conglomerates. This enables the bit to maintain its cutting structure integrity and drill longer intervals and prove to be cost effective.

The case studies presented in this paper show relevance to the laboratory test observations as to how shaped cutter can be developed for hard rock formation drilling and interfacial severity applications.

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### Nomenclature

<i>BHA</i>	= Bottomhole assembly
<i>PCD</i>	= Poly-crystalline diamond
<i>RPM</i>	= Revolutions per minute
<i>WOB</i>	= Weight on bit
<i>HFTO</i>	= High Frequency Torsional Oscillation
<i>MSE</i>	= Mechanical Specific Energy
<i>PDM</i>	= Positive displacement motors
<i>BHA</i>	= Bottom Hole Assembly

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