

PDC Bit Technology for the 21st Century

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Polycrystalline diamond compact bits have led the way to greater drilling efficiencies in many recent plays. However, as operators push the limits of depth, temperature and distance in pursuit of new reserves, they also push the limits of drillbit life and efficiency. Recent advances in cutter technology are enhancing bit performance and durability across a wider range of lithologies than was previously possible.

The modern drill bit is a product of years of refinement in materials and designs aimed at increasing rate of penetration, improving wear resistance and extending bit life. One of the most significant changes occurred in the 1970s, when a synthetic diamond material was used to create

the polycrystalline diamond compact (PDC) bit. Man-made, polycrystalline diamonds possess extreme hardness—similar to that of natural diamond, the world's hardest naturally occurring substance—with the strength and durability of tungsten carbide, which is used extensively in roller cone bits.

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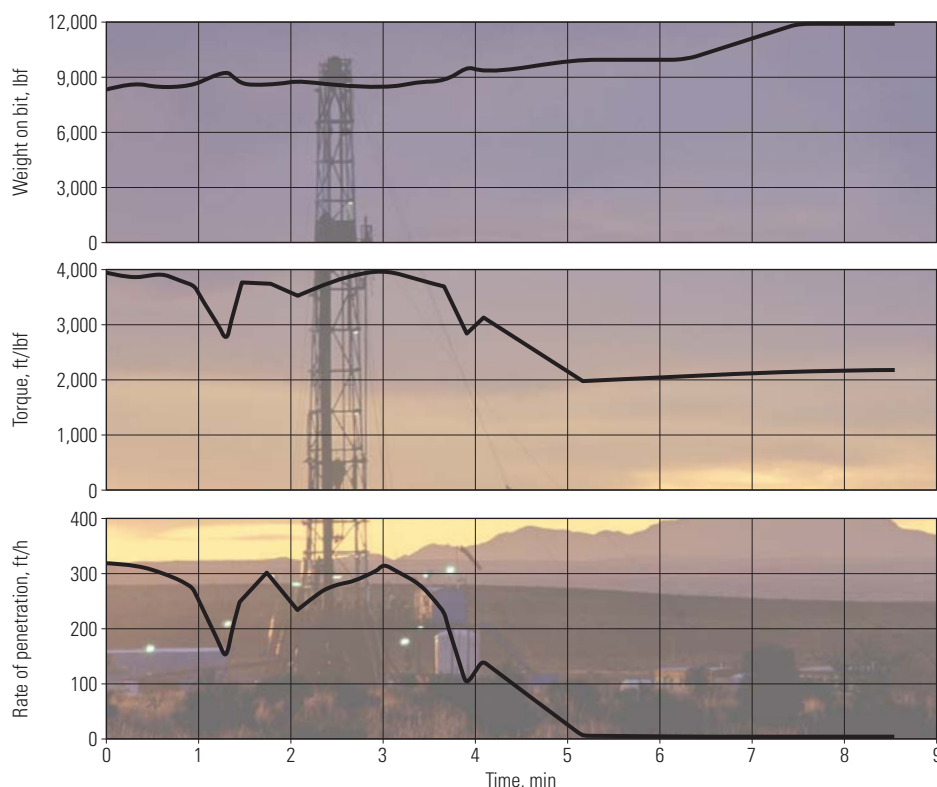
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1. Durrand CJ, Skeem MR, Crockett RB and Hall DR: "Super-Hard, Thick, Shaped PDC Cutters for Hard Rock Drilling: Development and Test Results," paper SGP-TR-188, presented at the 35th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA, February 1–3, 2010.
2. Durrand et al, reference 1.
3. Warren TM, Brett JF and Sinor LA: "Development of a Whirl-Resistant Bit," *SPE Drilling Engineering* 5, no. 4 (December 1990): 267–274.
4. Brett JF, Warren TM and Behr SM: "Bit Whirl: A New Theory of PDC Bit Failure," paper SPE 19571, presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, October 8–11, 1989.
5. Bit bounce most frequently occurs while drilling vertically through hard formations as slight axial displacements repeatedly lift the bit off bottom and slam it back down. Stick-slip is caused by friction buildup between the BHA and formation, which compels the bit to momentarily slow or stop turning. When torque within the drillstring overcomes these frictional forces, the BHA releases from the wellbore wall, causing the BHA and bit to spin as the drillstring rapidly unwinds. Bending, caused by placing too much downward force on the drillstring, creates lateral shocks when the drillstring is deformed enough to make contact with the wellbore.

For more on downhole shock and vibration and their effects on drillbit design: Centala P, Challa V, Durairajan B, Meehan R, Paez L, Partin U, Segal S, Wu S, Garrett I, Teggart B and Tetley N: "Bit Design—Top to Bottom," *Oilfield Review* 23, no. 2 (Summer 2011): 4–17.

Bit Performance Data



▲ End of a PDC bit run. Significant declines in rate of penetration (ROP) and drilling torque inevitably lead to increased weight on bit (WOB) and bit wear. (Adapted from Warren et al, reference 3.)



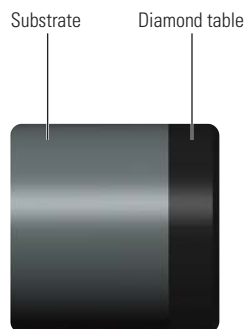
The introduction of PDC cutters and associated bit designs fundamentally changed the mechanics of drilling. Instead of gouging and crushing the rock, as does a roller cone bit, PDC bits use a transverse shearing motion. Although the three-cone roller bit dominated the industry for much of the 20th century, it may not be particularly suited for some of the challenges facing drillers today. High temperatures typical of deep formations and high rotary speeds produced by downhole drilling motors led to damaged seals, worn bearings and bit failure. Since the introduction of the fixed blade PDC bit, the industry has gradually moved away from roller cone bits.¹ By 2004, footage drilled by the PDC bit surpassed that of the roller cone bit.

Although PDC bits were used extensively throughout a range of drilling environments, in certain drilling applications, PDC bit performance pales in comparison to that of roller cone bits. For example, hard carbonates and abrasive sandstones can be problematic for any bit. In such formations, PDC bits tend to drill at a higher rate of penetration (ROP) than either roller cone or diamond-impregnated bits, but at some point, shearing efficiency declines and ROP decreases abruptly, which typically prompts drillers to increase weight on bit (WOB) to maintain ROP.

As WOB increases, PDC cutter edges wear flat, and drilling efficiency decreases further as

the worn bit starts crushing the rock rather than shearing it. Frictional energy generated by increased WOB heats the cutter, which leads to thermal degradation of the PDC.² When torque and ROP abruptly decline, the driller is forced to pull out of the hole to replace the worn bit ([previous page](#)).³

As manufacturers worked to improve PDC thermal characteristics, Amoco Production Company field tests conducted during the late 1980s revealed that impact loading caused by excessive downhole vibration was another significant contributor to PDC cutter wear and failure.⁴ Downhole vibrations are often linked to the phenomena of bit bounce, stick-slip and bending.⁵ These problems can be monitored and corrected



▲ Polycrystalline diamond compact cutter. Each polycrystalline diamond compact is made up of a diamond table (black) and a tungsten carbide substrate (gray). A nonplanar interface (not shown) between the substrate and the diamond table creates a strong bond between the two when the diamond table is sintered to the substrate.

from the drill floor. The same is not the case for bit whirl—another important contributor to downhole shock and vibration. To address this problem, bit manufacturers turned to their design engineers for a solution.

Bit whirl occurs when a bit's axis of rotation is not in line with the bit's physical center. Bit whirl produces severe lateral movement of the bit. During whirl, one of the cutters becomes an instantaneous center of rotation, such that the bit rotates about this contact point rather than about its central axis. The resulting asymmetric cutting action pushes one side of the bit against the borehole wall, producing an over-gauge hole and additional friction. As the bit rotates about this contact point, friction builds, and torque in the drillstring increases, which can force the bit to move backward relative to the surface rotation of the drillstring, or laterally, creating high-impact loads on the bit and BHA.⁶

To alleviate this problem, manufacturers initially developed variations on a PDC bit that used a large noncutting wear pad to slide the bit into the borehole wall and prevent walking, thus decreasing bit whirl.⁷ Since then, antiwhirl bit design has evolved considerably.

The drive to increase bit longevity led to numerous design modifications: thicker diamond layers, additional cutters, more blades, smaller cutters and increased back rake, or decreased contact angle, of the cutters. Materials research produced advances in diamond formulations and helped increase thermal stability. Improvements in the manufacturing process led to changes in diamond press engineering and sintering processes.⁸

Smith Bits, a Schlumberger company, recently introduced two innovations that are changing the ways in which PDC bits drill:

- a single conical diamond element placed at the center of the bit to create a PDC bit that produces a combination of shearing and crushing action
- rotating cutting elements, which distribute wear evenly on the cutter edge to extend cutter life beyond that of premium fixed PDC cutters.

This article discusses the development of the Stinger conical diamond element and the ONYX360 rolling PDC cutter. Case studies demonstrate how these new bit designs are expanding the application of PDC bits into challenging drilling environments while helping operators improve drilling efficiency and extend bit life.

PDC Basics: Design and Terminology

The PDC bit was a radical departure from the conventional roller cone bit. To capitalize on the shearing action of the polycrystalline diamond compact, bit designers developed a specialized cutting structure.

In a PDC bit, the compact is a disk made of polycrystalline diamond, synthesized by sintering diamond grit with a catalyst under high pressure and temperature. During the manufacturing process, the diamond grit—an aggregate of randomly oriented fine and ultrafine synthetic diamond particles—is fused with cobalt [Co] under extreme pressure and heat to produce a cylinder of polycrystalline diamond (see “One Step Further: PDC Manufacturing,” *page 52*). Unlike natural diamond [C], which fractures along crystallographic planes, polycrystalline diamond, with its randomly oriented synthetic diamond matrix, has no preferred cleavage planes, thus making the PDC cutter extremely hard and resistant to impact and wear. A shift to multimodal diamond grit—using a range of grit sizes that permits smaller particles to fill voids between large particles—has helped further increase wear resistance.

The cutter consists of two parts: a polycrystalline diamond table and its substrate (*above left*). PDC manufacturers refer to the flat cylinder of synthetic diamond as a table.⁹ The table is the part that comes in contact with the formation. Tables typically range in thickness from 2 to 4 mm [0.08 to 0.16 in.]. Some tables have a slight bevel that reduces stress on the cutter as it makes initial contact with the rock at the instant it starts to cut. Although the beveled edge can reduce bit aggressiveness, it helps increase durability and diamond table impact resistance.

The diamond table is sintered to a hard substrate composed of tungsten carbide [WC]. Unlike many substances, tungsten carbide is able to bond to diamond, so while the substrate gives structural support to the diamond table, it also provides a medium that can withstand brazing—a process used to mount the cutter to the bit.¹⁰ The substrate diameter conforms to that of the table and is typically about 1.3 cm [0.5 in.] across. The development of a nonplanar interface between the table and substrate helped reduce stress and strengthened the bond between the diamond and tungsten carbide.¹¹

A step change in extending longevity came with the invention of the leached PDC. The leaching process removes interstitial cobalt—a catalyst used in sintering the conventional PDC—from several microns of the diamond's outer surface. The Co is introduced to the PDC through the WC substrate during the high-pressure, high-temperature (HPHT) sintering phase of the manufacturing process. During sintering, Co melts and is forced into the diamond porosity, where a catalytic reaction produces intergranular diamond bonds. At high temperatures, however, Co also catalyzes the reversion of diamond to graphite, which weakens the PDC. Leaching Co from synthetic diamond improves its resistance to abrasion while reducing the effects of differential thermal expansion between diamond and cobalt.¹²

The cutters are mounted along the surface of the PDC bit by brazing the substrate to a blade. Three to eight blades—sometimes more—are arrayed along the outside of the bit, radiating outward from its nose (*next page, top left*). The number of blades varies according to the intended application, as does the number of cutters mounted to each blade. Bit designers must consider cutter number and placement when specifying depth of cut. Reducing the number of

6. Brett et al, reference 4.

7. Warren et al, reference 3.

8. Durrand et al, reference 1.

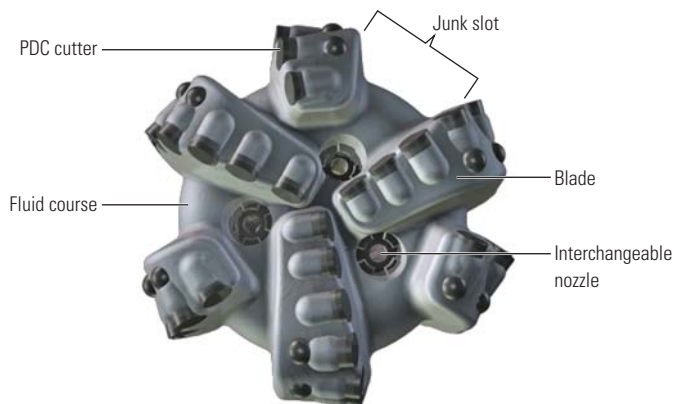
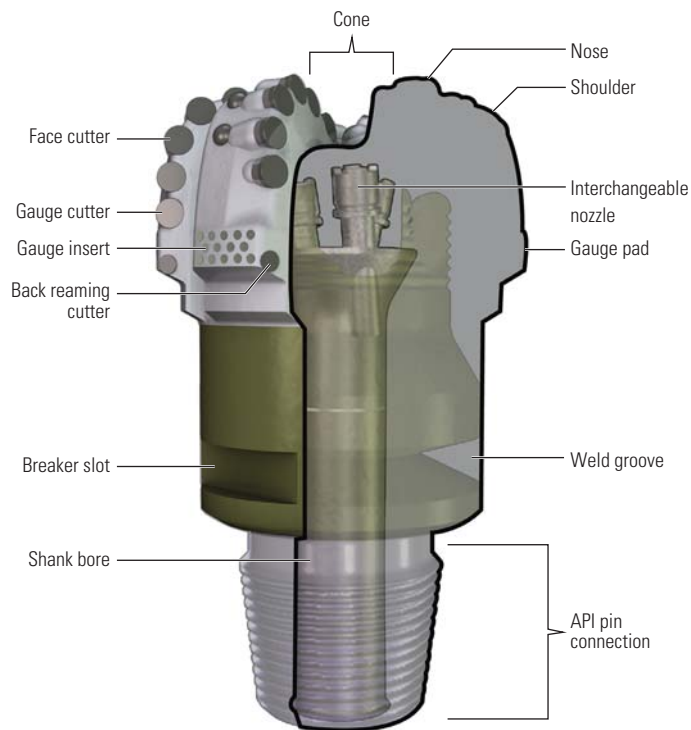
9. Gemologists define a table as the largest facet on a gem.

10. Brazing is a process, similar to soldering, in which a melted filler is used to join metals or ceramics together. Two work pieces are heated to a temperature higher than the melting point of the filler, but lower than the melting points of the work pieces. The melted filler is distributed between the close-fitting work pieces by capillary action. When the filler cools and solidifies, it joins the pieces together.

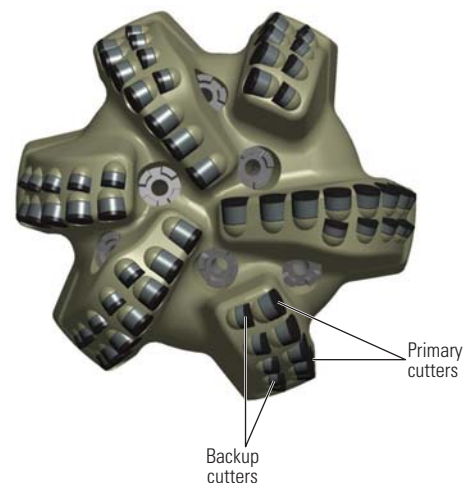
11. Clegg J. “Faster, Longer, and More-Reliable Bit Runs with New-Generation PDC Cutter,” paper SPE 102067, presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, September 24–27, 2006.

12. Durrand et al, reference 1.

13. Hardbanding is a manufacturing process in which an alloy coating is applied to an exposed metal surface to protect the metal from abrasive wear. The alloy used must be harder than the metal it protects.



^ PDC bit components. The most prominent features of the PDC bit are its blades and cutters. Various types of cutting structures are concentrated along the cone, nose, shoulder and gauge areas of the bit (*top*). Nozzles, junk slots and fluid courses (*bottom*) aid in removal of cuttings from the bit face.



^ Backup cutters. Some PDC bit designs include a second row of cutters. The two rows of cutters—primary and backup—reinforce each other to increase bit durability.

vary between cutters, depending on their position along the length of a blade. While back rake can limit depth of cut and penetration rate, it can be helpful in reducing bit vibration and wear.

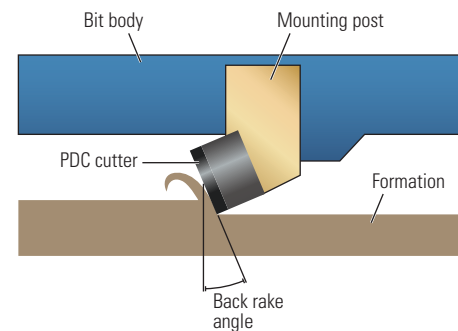
The body of a PDC bit is made from steel or from a matrix of tungsten carbide and an alloy to bind the matrix, which is sintered to a steel core. The selection of a steel or matrix bit body usually depends on the operator's intended application. The ductility and strength of steel make steel PDC bodies resistant to impact loading, but a steel body is less resistant to abrasion than a matrix body. Because steel is softer than tungsten carbide, hardbanding or other wear-resistant applications may be installed on certain parts of the bit to resist wear.¹³ The tungsten carbide matrix is available in a variety of formulations to provide resistance to abrasion or can be

(continued on page 54)

cutters tends to increase the depth of cut but also increases cutter wear. As a bit rotates, cutters near the side, or gauge, of the bit travel a greater distance than those near the bit center; therefore, to extend bit life, some designs reduce the spacing between cutters placed near the side of the bit. On some bits, two rows of cutters are brazed to each blade; backup, or secondary, cutters ride behind the primary cutters and may be

set deeper into the bit body. The secondary cutters engage the formation after the primary cutters have started to wear (*above right*).

Cutters are placed at an angle along the leading edge of the blade. This attack angle, or back rake, controls how aggressively the cutters engage the rock (*right*). Smaller angles of back rake are used in soft formations, but hard formations require a less aggressive bit and, thus, greater back rake. The back rake angle may also



^ Back rake of PDC cutter. PDC bits drill through formations by shearing the rock. Back rake angle controls how aggressively the cutter engages the rock.

One Step Further: PDC Manufacturing

A compact is a solid form created by pressing, or compacting, a finely ground powder inside a die. Some of the most common compacts are created by the pharmaceutical industry: Aspirin, vitamins and various medications are often manufactured in tablet form. These tablets start as powders, which are then compacted in a cold press.

For ceramics or metals, the process of creating compacts is taken one step further—in addition to pressure, heat is used to transform powder to solid. A blend of fine metallic or ceramic powder is placed in a die and compressed under high pressure. The compressed particles fuse together as heat is applied in a process known as sintering. Given sufficient heat, partial melting results in diffusion of atoms between granules, reduction of porosity and increase in density. The powder granules adhere and form a solid when cooled. The pressures and temperatures needed to make such compacts are created within the confines of a hot press.

Most metals can be sintered, as can many nonmetallic substances such as silica and even diamond. Some substances require an additional step beyond that of the conventional sintering process. In liquid-state sintering, a second component interacts with the powder during heating. The melting point of the second component is lower than that of the primary component. During sintering, the powder granules form a matrix while the second component melts to fill in the pore space between granules.

The production of synthetic diamonds also involves sintering. An ultrahigh-pressure, high-temperature belt press, invented by scientists at General Electric in 1954, led to the first commercial production of synthetic diamonds.¹ This press supplied the pressure and heat needed to convert carbon to diamond. Temperature and pressure varied depending on the carbon source and catalyst, but ranged

from 1,200°C to 2,400°C [2,200°F to 4,350°F] and 55,000 to 100,000 atm [5,570 to 10,130 MPa or 808,200 to 1,469,600 psi].²

General Electric invented the PDC cutter in 1971 and, after years of field testing, introduced the STRATAPAX line of PDC cutters in late 1976. To make the diamond powder used in the sintering process, thin circular layers of alternating graphite and cobalt were stacked in small cans and pressed to about 13,800 MPa [2 million psi] followed by resistive heating to about 1,500°C [2,700°F]. Molten cobalt, acting as a catalyst and solvent, dissolved the graphite and deposited a monocrystalline diamond grit.³

To produce a polycrystalline diamond compact, the diamond grit is packed in the press against a tungsten carbide–cobalt [WC–Co] substrate. The pressure is raised inside the press, thus compressing the diamond aggregate and increasing its density. The temperature increases, and when the cobalt in the substrate reaches its melting point, it is instantaneously squeezed into the pores between the diamond particles. The cobalt serves as a catalyst to create bonds between diamond particles and bind the diamond table to the substrate.⁴

In the years that followed, numerous companies developed synthetic diamonds, diamond bearings, polycrystalline diamond inserts, cutters and associated product lines. Two such companies were founded by a member of the team that invented the original belt press. In 1955, H. Tracy Hall left General Electric to launch Novatek, which now develops specialized electronics, metals and supermaterials. In 1966, he founded MegaDiamond, which now manufactures ultrahard products using diamond technology. MegaDiamond was later acquired by Smith Bits, which in turn was acquired by Schlumberger. Both Novatek and MegaDiamond supply diamond bit cutters to Schlumberger through its Smith Bits subsidiary.

At Novatek, Hall developed the tetrahedral press in 1957 and the cubic press in 1966. A solid unitary-frame press, developed in 1999, is now in its fifth generation ([next page](#)). This computer-controlled press has a cubic frame and six instrumented cartridges—each with an anvil capable of exerting more than 35 million N [8 million lbf]. The 4,000-tonUS [3.6-million-kg] press can subject workpieces—cubic cells with raw materials embedded in a pyrophyllite shell—to temperatures up to 2,300°C [4,200°F] and pressures exceeding 7,500 MPa [1 million psi]. A computer interface allows the operator to control the press from a separate location and precisely monitor anvil positions. Novatek uses this advanced press technology to manufacture the Stinger conical diamond element. The polycrystalline diamond on this conical element is approximately twice as thick as the diamond layer on a conventional PDC cutting element; its shape is optimized for strength in axial compression to deliver high point loading on the formation.

The ONYX 360 rolling PDC cutter is produced by MegaDiamond. The company produces an extensive line of engineered polycrystalline diamond products for drilling and mining, including PDC shear elements for fixed cutter bits and diamond-enhanced

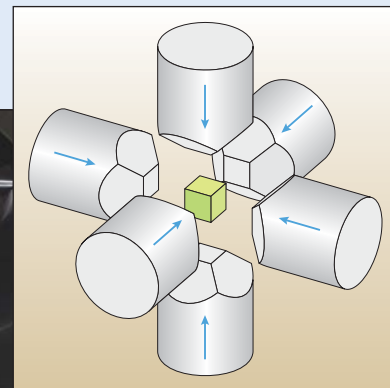
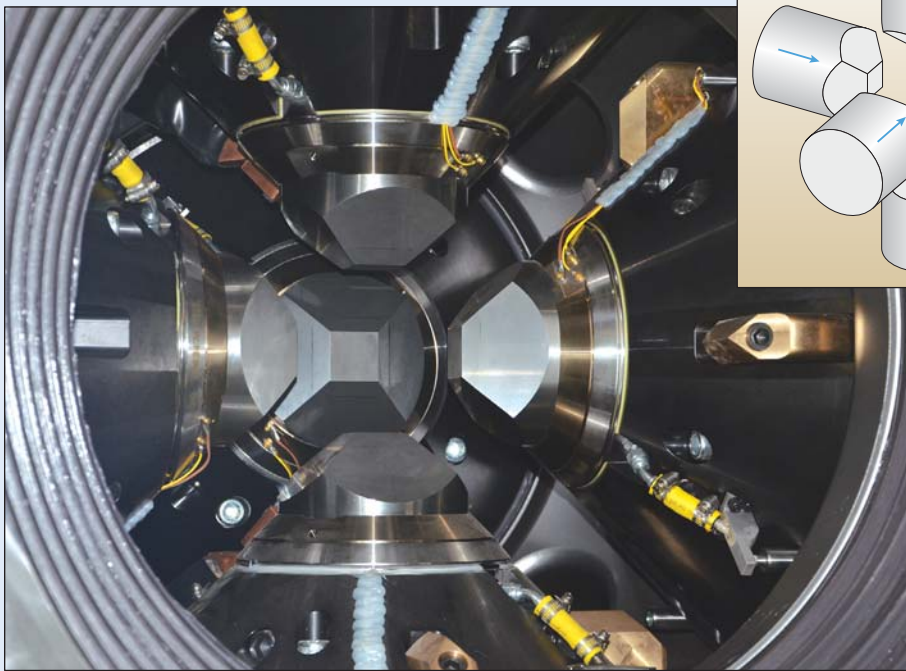
1. Hall HT: "Ultra-High-Pressure, High-Temperature Apparatus: The 'Belt,'" *The Review of Scientific Instruments* 31, no. 2 (February 1960): 125–131.

2. General Electric researchers succeeded in transforming carbon to diamond using graphite, carbon black and sugar charcoal as the carbon source; a wide range of catalysts were used, including chromium, manganese, iron, cobalt, nickel, ruthenium, rhodium, palladium and platinum.

Bovenkerk HP, Bundy FP, Hall HT, Strong HM and Wentorf RH: "Preparation of Diamond," *Nature* 184, no. 4693 (October 10, 1959): 1094–1098.

3. Besson A, Burr B, Dillard S, Drake E, Ivie B, Ivie C, Smith R and Watson G: "On the Cutting Edge," *Oilfield Review* 21, no. 3 (Autumn 2000): 36–57.

4. Bellin F, Dourfaye A, King W and Thigpen M: "The Current State of PDC Bit Technology," *World Oil* 231, no. 9 (September 2010): 41–46.



▲ Cubic press. The center of the computer-controlled press is surrounded by six anvils (five of which are shown), each capable of exerting more than 35 million N. A workpiece (green, *inset*) is placed within the center of the press, then the anvils simultaneously press against it.

inserts for roller cone bits and percussive mining bits.

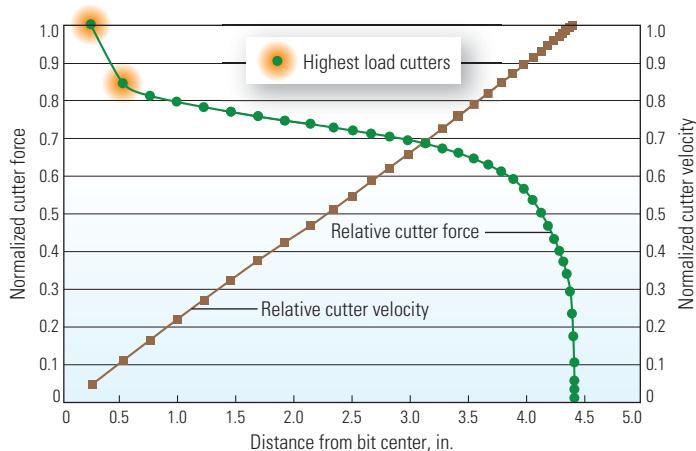
The company operates three types of HPHT presses: the belt press, piston-cylinder press and cubic press. To manufacture polycrystalline diamond components, MegaDiamond engineers determine specific material and wear demands for each customer's application, then apply the appropriate press technology to produce the diamond grades needed for the job. Each press is capable of generating the ultra-high pressures—greater than 5,500 MPa [800,000 psi]—and high temperatures—1,500°C [2,700°F]—required to sinter polycrystalline diamond products, and each has advantages regarding sintering characteristics and the properties imparted to the final product.

The belt press is modified from the original HPHT design of the 1950s. To generate the extreme pressures required to sinter polycrystalline products, the press utilizes two carbide punches that converge on a high-pressure capsule contained within a carbide die. The modern belt press is well suited for producing large diameter products or multiples of smaller products. The name is taken from the concentric, shrink-fitted steel “belts” that prestress the inner carbide die, allowing it to withstand the immense internal pressure.

The piston-cylinder press, similar to a belt press, uses a high-pressure capsule contained within a cylindrical bore. Two free-floating carbide pistons pressurize the capsule when a load is applied by conical carbide anvils. The carbide die is supported by radial hydraulic pressure rather than by a series of steel belts.

The cubic press is the most current design. It relies on six carbide anvils attached to massive hydraulic cylinders converging simultaneously on a cube-shaped, high-pressure capsule. This triaxial system generates isostatic high pressures suited for sintering products with complex 3D geometries. As with all MegaDiamond presses, the cubic system is integrated with a computerized control system to ensure optimal and consistent pressure, temperature and time during sintering.

Laboratory facilities at Novatek and MegaDiamond permit scientists and engineers to evaluate polycrystalline diamond performance in a variety of functional tests, simulating real-world conditions. Data gathered in the test laboratory are fed to an iterative design cycle process, culminating in improved performance at the wellsite.



▲ Cutter force and distance from the bit center. Cutters at the cone of a bit (orange circles) are subjected to the highest force (green), experience the lowest velocity (brown) and typically remove the smallest volume of rock.

manufactured to suit a particular formation or drilling application. The matrix material can withstand relatively high compressive loads but is more brittle than steel and has a lower resistance to impact loading than steel.

A Central Element

To improve bit performance in a wider range of environments, bit manufacturers are testing PDC bits in abrasive and interbedded formations, where penetration rates and bit life commonly cause problems for drillers. These types of formations are difficult to drill, regardless of the type of

bit used. Because vibration-induced impact damage is the primary mechanism for reducing bit life and ROP, bit manufacturers sought to develop a more stable fixed cutter bit that would reduce vibration and shock in these types of formations. Engineers with Smith Bits, working in conjunction with bit designers from Novatek, experimented with cutter placement and count to improve drilling efficiency and mitigate vibration. They focused on the problematic cone, or central cutting area, of a conventional PDC bit face.

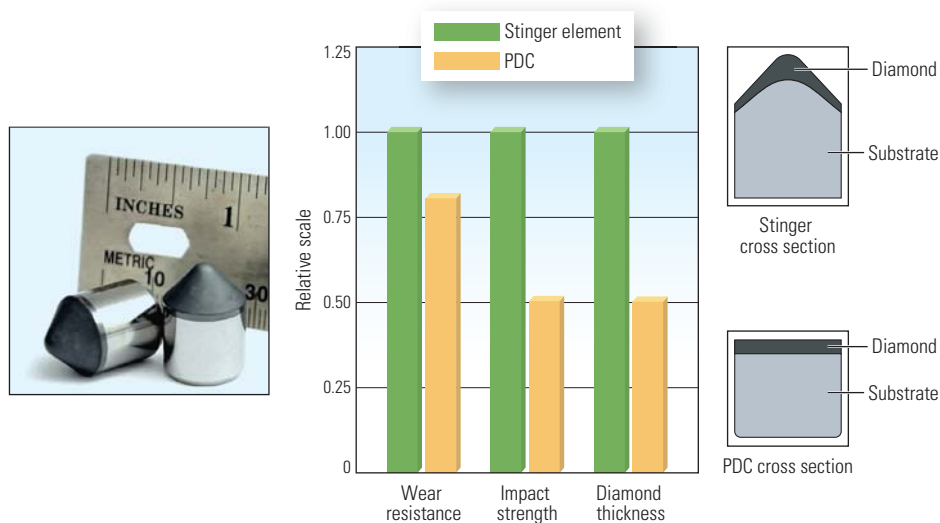
When a conventional PDC bit is used, the centermost portion of the borehole can be difficult to

remove. Because the velocity of conventional PDC cutters decreases with proximity to the center of the cutting structure, the cutters are least effective at removing rock from the center of the borehole, especially in hard formations.¹⁴ Central cutters are subjected to the highest axial loads on the bit and can create large bit torque fluctuations, which occur when drillers change weight on bit or rotary speed, or when they drill through changing lithologies that have differences in unconfined stress. The torque variations alter the dynamic response of the bit, exposing it to damaging shock and vibration.¹⁵ These phenomena create an inefficient shearing mechanism at the center of the conventional PDC bit (left).

This characterization of the cone area led to development of the Stinger conical diamond element (below left). This conical diamond element (CDE) has an ultrathick polycrystalline diamond layer. The CDE is positioned at the center of the bit with the conical tip facing the rock. Its conical geometry and thick diamond structure create a robust and durable cutting element that delivers high point loading for effective formation fracture.

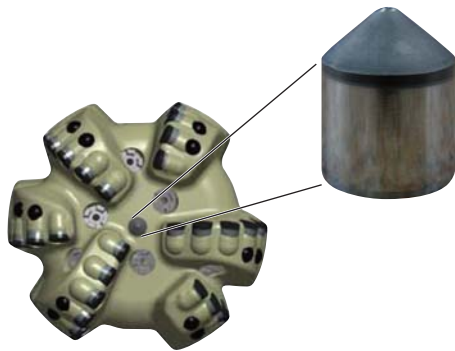
To evaluate CDE potential for improving penetration rates and increasing total footage, bit engineers subjected the CDE to testing on a vertical turret lathe (VTL). This apparatus uses a test bed of granite or quartzite to measure the cutter's ability to fracture rock under varying conditions. Testing on the lathe showed the CDE had greater cutting efficiency and wear resistance than standard PDC cutters. For example, at a 5,300-N [1,200-lbf] threshold, a 0.5-mm [0.02-in.] depth of cut resulted in a 70% increase in cutting efficiency compared with that of the baseline PDC cutter; at 1.3-mm [0.05-in.] depth of cut, the CDE cutter showed a 35% increase.¹⁶

The next challenge was to incorporate the CDE into a PDC bit design. Smith engineers used finite element analysis (FEA) to design the bit. The IDEAS integrated drillbit design platform helped engineers selectively remove inefficient



▲ Conical diamond element (CDE). The Stinger CDE (left) is manufactured in an advanced synthetic diamond press to produce a layer of diamond that is substantially thicker than that of a conventional PDC cutter (right). The polycrystalline diamond material has been engineered to provide a higher level of impact strength and resistance to abrasive wear (graph, center).

14. Azar M, White A, Segal S, Velvaluri S, Garcia G and Taylor M: "Pointing Towards Improved PDC Bit Performance: Innovative Conical Shaped Polycrystalline Diamond Element Achieves Higher ROP and Total Footage," paper SPE/IADC 163521, presented at the SPE/IADC Drilling Conference and Exhibition, Amsterdam, March 5-7, 2013.
15. Azar M, White A, Velvaluri S, Beheiry K and Johnny MM: "Middle East Hard/Abrasive Formation Challenge: Reducing PDC Cutter Volume at Bit Center Increases ROP/Drilling Efficiency," paper SPE/IADC 166755, presented at the SPE/IADC Middle East Drilling Technology Conference and Exhibition, Dubai, October 7-9, 2013.
16. Azar et al, reference 15.



^ Stinger CDE. After cutting structures are removed from the bit center (*left*), space is created for placement of a CDE (*right*). This space also enables development of a small rock column that is easily crushed by the CDE.

PDC cutters and scale back the blades on which they were mounted. This resulted in a void at the center of the bit. As drilling proceeds, this void permits a small column of rock to develop at the bit's center. As this rock column forms, it becomes less confined. Designers positioned the CDE at the center of the bit (*above*). As the uncut rock column builds in height, the Stinger element imposes a point load on the column to fracture and crush it while the bit drills ahead.

Engineers also used FEA software to investigate the stress field at the precise point that the Stinger element indents the formation. Their study confirmed that, compared with standard PDC cutters, the Stinger CDE required less force at the contact point to cause fracture generation within the unconfined rock. In addition, the Stinger element contributes to bit centralization, thus reducing the potential for damaging vibrations.

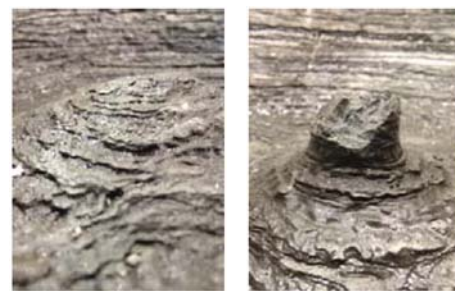
Smith engineers also needed to modify the bit nozzle orientation to efficiently clean and cool the new cutting structure. Using fluid dynamics software, they performed a hydraulic analysis in which nozzle positions were adjusted to enhance cuttings removal and cleaning of the conical element and borehole.

Full-scale testing of a CDE-equipped bit was conducted in a pressurized drilling simulator to validate the results of a 4D modeling study. The testing corroborated earlier experimental conclusions, whereby a modified bit created a stress relieved rock column that was crushed by the Stinger element at the center of the hole (*above right*). These tests also revealed that CDE-equipped PDC bits generate much larger drill cuttings than do standard PDC bits, thus facilitating better rock characterization by geologists or mud logging personnel.

Modeling and testing results convinced engineers that a single CDE positioned at the center of the bit would improve ROP performance and enhance dynamic stability. They selected an 8½-in. PDC bit for field testing using a Stinger conical element positioned at the bit's center. Field tests were conducted in the US; PDC bits with Stinger CDEs were successfully run in the Williston basin of North Dakota, in the Cotton Valley Formation of East Texas and in the interbedded sand and shales of the Wasatch Formation in Utah. Each test demonstrated substantial gains in ROP and reductions in bit wear.

Following successful runs in North America, a PDC bit with a Stinger CDE was tested in Zubair field, Iraq. Vibration problems were causing low ROP and inconsistent drilling performance. Formations encountered in the 12¼-in. hole section included medium-to-hard carbonates and interbedded intervals that had caused stick-slip and lateral vibration problems in offset wells. These conditions forced the operator to slowly control drill through the interval, thus compromising ROP.

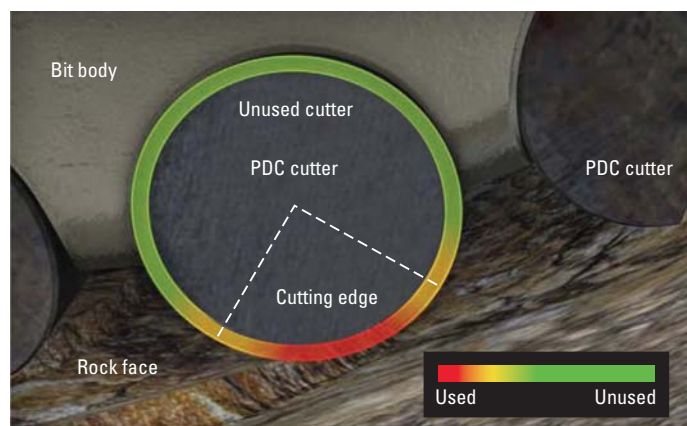
To solve the problem, a 12¼-in. 6-bladed PDC bit with 16-mm [0.63-in.] cutters was selected, and a CDE was installed at the center of the bit. The modified bit, run on a steerable BHA, drilled 595 m [1,950 ft] of hole from casing shoe to TD in one run, achieving an ROP 29% greater than that of the best offset run of 18.5 m/h [60.7 ft/h] and 56% better than the average ROP of 15.3 m/h [50.2 ft/h] previously attained while drilling three offset wells. The bit also exhibited more stable behavior, drilling with less stick-slip and lower vibration levels than those experienced in offset wells.



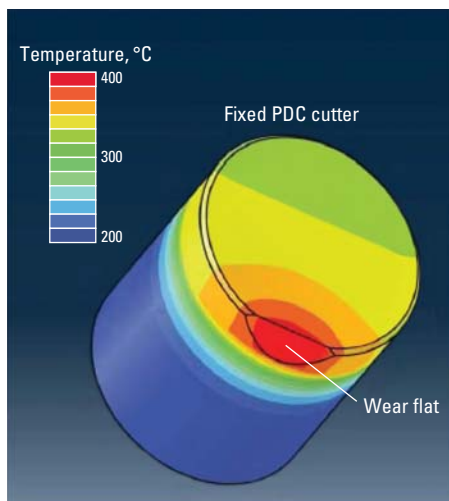
^ Results of full-scale testing. Inefficient cutters at the center of a standard PDC bit allow development of a central mound of rock (*left*). However, because the central cutters have been removed, a small column of stress-relieved rock develops (*right*). When a Stinger CDE engages this rock column, it fractures and crushes the rock.

Cutter Revolution

In many applications, PDC bits have demonstrated significant advantages over roller cone bits for extended footage capabilities and high ROP. However, hard and abrasive formations—which pose some of the toughest conditions that any bit might face—typically cause significant wear on fixed shearing elements. In such environments, the fixed cutter of the PDC bit can chip, causing drilling efficiency to decline. On a PDC bit, the cutter is fixed in place and most of it is shielded within the body of the blade itself—only a small portion of the diamond table contacts the formation (*below*). As the cutter shears the rock, the exposed portion of the cutter gradually grows dull through abrasive action.

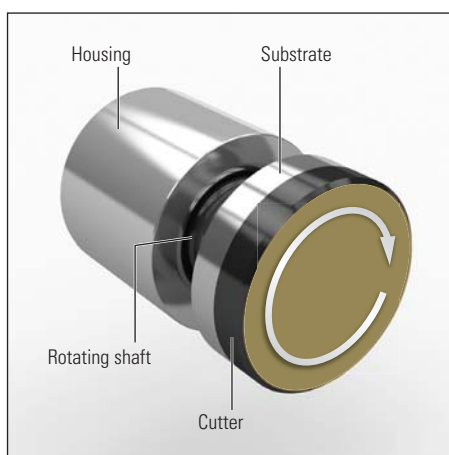


^ PDC cutting surface. More than 60% of the circumferential edge of a fixed PDC cutter is retained within the body of the bit and goes unused. The actual amount used will vary with cutter size, back rake and depth of cut.



^ Heat-induced cutter degradation. Finite element analysis shows how frictional heat concentrates along the cutter edge, where it contacts the rock; friction and heat aid in creating a wear flat.

An FEA evaluation of fixed cutter wear showed that frictional heat concentrates where the cutter edge contacts the rock (above). The combination of high temperature, abrasion and WOB eventually causes the cutting edge to wear flat. The resulting surface, known as a “wear flat,” is subjected to an even higher degree of frictional heat, which induces more wear as the bit continues to drill.



^ ONYX 360 rolling cutter. The ONYX 360 cutter shaft is fully contained within an integrated housing to ensure continuous rotation and cutter retention during drilling. The bit’s drilling force, coupled with the cutter’s orientation relative to the rock face, causes the cutter to rotate. As a result of rotation, the entire edge of the cutter is used, thus spreading wear more evenly along the cutting edge.

Mechanical loading, in combination with concentrated heat buildup at the cutting edge, can weaken the diamond bonding and damage the cutter edge. As wear progresses through the synthetic diamond table, it eventually reaches the tungsten carbide substrate, causing a noticeable reduction in shearing efficiency and ROP.

Because heat buildup causes accelerated cutter wear, and more wear generates even more heat, bit designers sought to break this cycle by keeping the cutting edge both cool and sharp. To manage heating by reducing friction at the cutting edge, Smith engineers created the industry’s first cutter that enables the diamond table to fully rotate while drilling. The 360° rotation reduces localized wear by keeping the cutter edge significantly cooler and sharper than fixed cutters. Bit designers mounted the cutter onto a shaft and fitted the assembly into a tungsten carbide sleeve that enables the cutter to rotate freely.¹⁷ The sleeve is installed in a housing that is brazed into the bit blade to secure the cutter while it rotates (below left). The cutter’s orientation in the bit blade, relative to its contact angle with the formation, creates a rotational force that causes the cutter to spin on its shaft as the bit rotates.

The ONYX 360 cutter is designed for high-wear areas on the cutting structure and is mounted only at certain locations along a bit. Using the IDEAS integrated drillbit design platform, Smith engineers mapped the areas of highest wear on a PDC bit and positioned the ONYX 360 rolling cutter there. For example, wear flats often occur on cutters along the shoulder area of a bit, where high velocity at the outer edge of the bit and the relatively large volume of rock removed by these cutters cause accelerated cutter degradation. By placing these low-wear, sharp-edged cutters at high-wear locations, bit designers have seen improved durability and sustained ROP across longer intervals. Placement of the ONYX 360 cutters varies for each bit, depending on such factors as bit size, blade count and type of lithology drilled.

The ONYX 360 cutter has been tested on a granite cylinder using a VTL. Vertical, tangential and radial forces were imposed on the cutter and recorded during the test. The test provided the basis for comparing the performance of the ONYX 360 cutter with that of a premium fixed cutter (next page, top left). During the test, the fixed cutter required increased force—from 200 to 1,200 lbf [900 to 5,300 N]—to maintain a con-

stant depth of cut as it wore. The rolling cutter required a relatively low and gradual weight increase, starting at 200 lbf, with gradual increases to 600 lbf [2,670 N], while depth of cut remained constant.¹⁸ This test demonstrated that the ONYX 360 cutter required less force to maintain a consistent depth of cut while removing more rock volume than the fixed cutter removed. Visual inspection of the cutters showed that the edge of the rolling cutter was slightly rounded, while the fixed cutter had a 0.12-in. [3-mm] wear flat.¹⁹ Because the rolling cutter remained sharper longer and dissipated heat better than the fixed cutter, it was able to shear more rock with less wear than the fixed cutter could.

Put to the Test

During the course of drilling an extended lateral section, an operator developing a field in Hemphill County, Texas, had to contend with the highly abrasive Granite Wash formation. This formation, a mix of disaggregated granite and its constituent feldspar and quartz grains, is formed from the remnants of intrusive igneous rock that was eroded and deposited downstream from its source. It is hard, abrasive and tough on bits. While drilling the 6½-in. diameter horizontal section, the operator was plagued by poor PDC bit performance. Cutter damage and abrasive wear reduced ROP to unacceptable levels and forced the driller to make frequent trips for new bits, thus adversely affecting project economics.

To solve this problem, the operator elected to mount a 6½-in. PDC bit equipped with seven ONYX 360 rolling cutters as part of a steerable BHA. This bit successfully drilled out the casing shoe then made 1,562 ft [476 m] of horizontal

17. Zhang Y, Burhan Y, Chen C, Tammineni S, Durairajan B, Mathanagopalan S and Ford R: “Fully Rotating PDC Cutter Gaining Momentum: Conquering Frictional Heat in Hard/Abrasive Formations Improves Drilling Efficiency,” paper SPE 166465, presented at the SPE Annual Technical Conference and Exhibition, New Orleans, September 30–October 2, 2013.

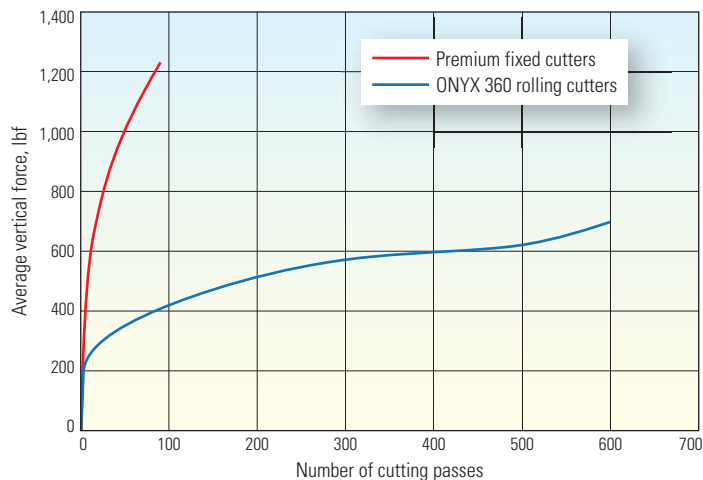
18. Zhang et al, reference 17.

19. Zhang Y, Baker R, Burhan Y, Shi J, Chen C, Tammineni S, Durairajan B, Self J and Segal S: “Innovative Rolling PDC Cutter Increases Drilling Efficiency Improving Bit Performance in Challenging Applications,” paper SPE/IADC 163536, presented at the SPE/IADC Drilling Conference and Exhibition, Amsterdam, March 5–7, 2013.

20. Zhang et al, reference 19.

21. Bruton G, Smith M, Mueller L and Ford R: “Constructing Difficult Colony Wash Lateral with Innovative Rolling Cutter Technology Improves Drilling Performance,” paper IADC/SPE 167956, presented at the IADC/SPE Drilling Conference and Exhibition, Fort Worth, Texas, March 4–6, 2014.

22. The Smith Bits DRS drilling records system is an extensive library of bit run information. Initiated in 1985, this database contains more than 3 million records from oil and gas fields around the world.



^ Results of vertical turret lathe tests. The ONYX 360 rolling cutter (blue) requires substantially less vertical force to drill a longer distance, enumerated as the number of cutting passes, compared with that required for a premium fixed cutter (red).

hole through the Granite Wash at an ROP of 24.79 ft/h [7.6 m/h], or 44% faster than that of the best fixed cutter bit previously used in that field. This bit was just one of more than 70 bits equipped with the rolling cutter to drill the Granite Wash formation. A statistical review of bit performance showed an average of 56% more footage drilled compared with results in 450 offset runs drilled with fixed cutter bits.²⁰

In another Granite Wash well, Chesapeake Operating Inc. ran PDC bits equipped with ONYX 360 cutters to drill a 6½-in. hole section.²¹ A review of the DRS drilling records system database shows that of 42 wells drilled within a 2-mi

[3-km] radius of the Chesapeake well, only two had a 6½-in. lateral section drilled through the Granite Wash formation using only PDC bits.²² The bits used in those two wells employed fixed PDC cutters. A performance analysis showed that bits equipped with the ONYX 360 rolling cutter demonstrated significant increases in durability and ROP compared with the fixed cutter bits. PDC bits with rolling cutters drilled an average 30% more footage than fixed cutter bits in the first well and 75% more than in the second well. The rolling cutter bits drilled the 6½-in. section with four fewer bit trips, saving five days of rig time through that interval.

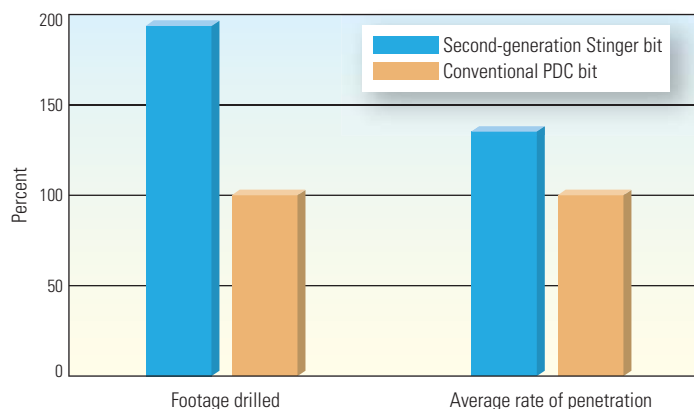
Raising the Bar

PDC bits equipped with Stinger conical diamond elements are helping improve ROP in many of today's challenging wells worldwide. Bits fitted with ONYX 360 rolling cutters are delivering unmatched performance in abrasive lateral applications such as those in wells from the central US. Operators who have tried these specially equipped bits are requesting them for use in upcoming wells.

Successes in the field are speeding the evolution of diamond cutting elements for PDC bits. Already, a new generation of PDC bits is being tested with multiple Stinger CDEs, spread across the entire profile of the bit. This second generation of Stinger bits has been subjected to harsh conditions, particularly in hard, interbedded formations that can damage the cutting structures of conventional PDC bits. During the first 100 runs, these bits have proved their reliability downhole, drilling more than 90% farther than standard bits and resulting in fewer trips to change bits (below left).

With additional development, innovations in polycrystalline diamond bit technology will continue to change the way the industry drills and expand the range of PDC applications. The resulting gains in ROP and bit life are expected to further reduce drilling costs and positively impact financial viability of difficult drilling prospects.

—MV



^ Comparison of drilling efficiency relative to the conventional PDC bit performance. The second generation of Stinger bits showed marked improvements in footage drilled and ROP.