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# The current state of PDC bit technology

## Part 3 of 3: Improvements in material properties and testing methods are being pursued to make PDC the cutter of choice for an increasing variety of applications.

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The first two installments of this three-part series discussed the early commercial history and technical challenges encountered in the manufacture of polycrystalline diamond compact (PDC) cutters and bits, the use of cutter leaching to improve resistance to thermal wear, and PDC cutter testing and qualification methods. This final article discusses selection of the proper PDC cutter for various bit applications. This is followed by a preview of future PDC developments, including enhanced substrate properties and cobalt management, alternative diamond manufacturing methods, and newly developing cutter testing methods.

## CUTTER SELECTION

Since the first PDC cutters were introduced in the 1970s, tremendous technological advances have been made. Changes in HPHT press technology have improved the sintering capability, yielding better diamond-to-diamond bonding and diamond-to-substrate bonding. Better bonding results in less cutter breakage and delamination.

Changes in the geometry at the interface of the diamond table and carbide substrate resulted in changes in the residual stress, resulting in thicker diamond tables and increases in diamond volume. In the field, these translated to higher wear life without increases in cutter breakage. The PDC cutter with a non-planar interface became the industry standard for many years. Variations in diamond grain size and interface provided bit suppliers the extra performance to be competitive.

Almost as soon as PDC cutters were invented, the dangers of thermal damage were recognized. PDC with the cobalt removed from the diamond table was one attempt at mitigating the problem. Another was replacing the cobalt with silicon carbide. Because of the limitations associated with attaching these materials to the bit, such as weakening of the polycrystalline diamond, these attempts were only partially successful.

Then, in 1983, two researchers with Sumitomo leached a thin layer of the PDC diamond table of a regular PDC insert. In their tests, they achieved a dramatic increase in performance. However, their invention languished until about 2000. With more modern diamond table understanding, bit suppliers applied this technique to PDC for rock drilling. PDC cutters treated in this manner, suitable for highly abrasive formations where thermomechanical wear is expected, now form a large category of what the industry deems a premium cutter. They are commonly called “leached” cutters.

In another effort, researchers at US Synthetic applied a thermally stable layer to a carbide substrate. To make this cutter type, a thin polycrystalline diamond layer is leached of its cobalt. Then the layer is placed on a carbide substrate and repressed in the HPHT press. The process yields a thermally stable layer attached to a carbide substrate. This cutter type also languished until the mid-2000s when, armed with more modern presses and understanding, researchers made a more robust version. This process, commonly called the “two-step” process, now forms another category of premium cutter. The diamond table goes through the HPHT press twice: once for its original sintering cycle, and a second time to join the layer to the carbide substrate.

Within the three categories above, there are many variants. The properties of a PDC cutter can be varied by altering grain size, interface and post-sintering treatment. In addition, each PDC manufacturer has the variances of its manufacturing process and experience. The result is a wide variety of PDC cutters on the market.

The position on the bit face can also affect a PDC cutter’s performance. For example, PDC cutters in the center have a large cross-sectional area of cut, but a slow cutting speed. PDC cutters on the flank of the bit have high cutting speed but a small area of cut. In addition, secondary cutters and gauge cutters have different performance requirements.

Faced with the wide variety of cutters on the market, how does the bit supplier optimize performance and remain competitive? The formations and drilling conditions will drive the bit selection. The astute applications engineer will understand the cutters at his disposal and requirements of the bit design and choose accordingly.

PDC cutters can be categorized by their abrasion resistance, impact resistance and thermal abrasion resistance. These three properties form the basis of the selection criteria. Unfortunately, it is difficult to get all three properties maximized in one cutter variant. The applications engineer must select the best cutter for the job, without risking other failure modes and without wasting money.

A cutter that is highly abrasion resistant is characterized by fine diamond grain size in a well-sintered part. Abrasion resistance is typically measured in the lab by cutting granite or sandstone with a coolant and measuring the rate of wear. Typical applications for this type of cutter are sharp sandstones of moderate to low compressive strength. The drilling interval and bit design will encourage drilling stability so that impact damage is minimized.

A cutter that is highly impact resistant is characterized by a coarse grain size in a well-sintered part. The diamond table interface will be designed to lessen cracking from impacts. Impact resistance is measured by drop tests or other diamond table strength measurements. Typical applications for this type of cutter are interbedded formations or bit designs with less drilling stability. Another application for this type of cutter is

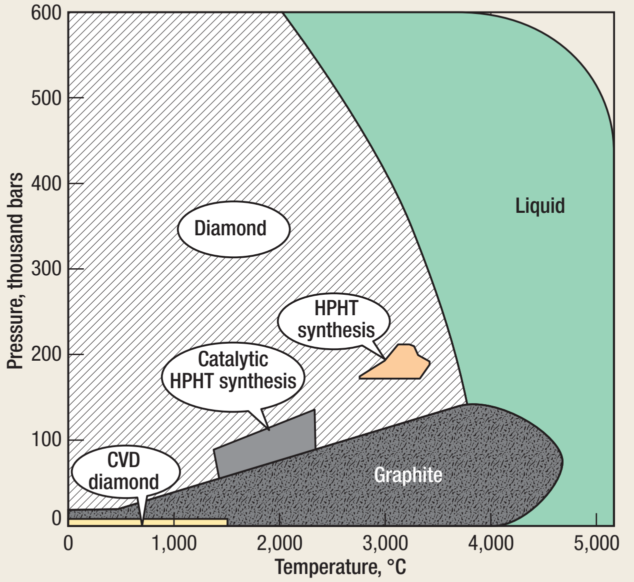

**Fig. 1.** Carbon diamond phase diagram showing higher pressures and temperatures required for diamond synthesis without catalysts. Adapted from F. P. Bundy of General Electric, courtesy of Diamond Innovations and Varel International.

where its position on the bit leads to the expectation of impact—such as cutters in secondary rows and or gauge cutters and trimmers.

In recent years, the application of PDC bits has broadened to include applications that require resistance to thermomechanical abrasion. PDC cutters of this type will be highly abrasion resistant with an additional level of thermal stability. They are characterized by a fine diamond grain size in a well-sintered part, with the residual cobalt in the diamond table either partially or totally removed. The cobalt can be removed either before or after sintering. Typical applications for this type of cutter include sharp sandstones of high compressive strength.

## FUTURE DEVELOPMENTS

Improvements in substrate properties, diamond material properties and testing methods are all being pursued with the goal of making PDC cutters and bits the tools of choice for an increasing number of application types.

**Substrate properties/cobalt management.** The tungsten carbide substrate of a PDC cutter is by definition an integral component of the cutter and is a key contributor to the overall application and performance of the PDC. The substrate acts as a growth platform for the creation of the polycrystalline diamond layer in the HPHT press and supplies the needed surface for the mounting of the PDC on a bit head. The substrate also acts as a transition layer between the extremely brittle diamond layer and the significantly less brittle bit body. This is the case whether the bit body is steel or matrix. This transition function helps the diamond layer better absorb impact loads generated during drilling.

Substrates are composed of tungsten, carbide and cobalt. Within the substrate, the cobalt adds fracture toughness. Tungsten carbide grades are generally categorized as being tougher when they have a greater cobalt content, and as more abrasion resistant when they have a lower cobalt content. PDC cutter manufacturers and, ultimately, bit builders have typically employed substrates containing a uniform gradation of cobalt in a percentage geared toward balancing fracture toughness and abrasion resistance.

Research efforts are underway to alter the substrates in such a way as to overcome this traditional tradeoff. These efforts are geared toward improved grain growth control in the manufacture of the substrate and in the gradation of cobalt content through the substrate. If, for example, the outer shell of the substrate can contain a lower percentage of cobalt than the substrate's core, then the outer portion of the substrate will be more erosion resistant where it is required to be. The inner core of the substrate in this case contains a higher cobalt content to provide the overall substrate with the requisite fracture toughness required of the drilling PDC.

Three possible ways of achieving these substrate properties are being explored, the first of which is a diffusion sintering process. Creating functionally graded tungsten carbide via this diffusion sintering process involves migrating atoms of cobalt from one end of the substrate to the other end while migrating atoms of carbon in the other direction, which results in a substrate that is functionally graded across its length. This can supply a substrate that is harder, for example, at the diamond layer end and softer at the distal end, creating an improved transition effect across the length of the substrate.

A second method being explored is referred to as imbibition. In this method, an existing tungsten carbide substrate is selectively masked off with a relatively impervious material such as boron nitride or aluminum oxide. The unmasked areas are brought into contact with a preferred imbibition material, in this case cobalt. The assembly is run through a thermal cycle, which allows the cobalt imbibition material to diffuse into the unmasked areas of the target substrate, creating zones rich in cobalt. This method offers myriad opportunities to modify cobalt-rich zones within the substrate to improve performance.

The third method that is being explored is a high-energy mechanical surface treatment of a tungsten carbide substrate. This approach masks off the diamond table of a PDC cutter to protect it from damage. The substrate is then subjected to a high-velocity shot peen with tungsten carbide beads. This method drives cobalt from the outer treated areas into the core of the substrate, enriching the core and depleting the outer surface to achieve the preferred cobalt gradation.

Another area of improvement of tungsten carbide properties that is being explored is microwave sintering. Traditional methods of sintering tungsten carbide cobalt bodies have involved high pressures and temperatures such as found in a hot isostatic press (HIP). When sintered in an HIP furnace, the tungsten carbide experiences grain growth that degrades the mechanical properties of the produced substrates. Microwave sintering is capable of producing tungsten carbide cobalt inserts with highly uniform, more densely packed fine grain structures that have improved mechanical properties compared with traditionally sintered parts. Added benefits of the microwave sintering method include faster sintering speeds and lower costs.

**Diamond.** Several alternatives to the polycrystalline diamond material traditionally used in PDC cutters are under development. The first of these is the two-step process discussed above, which was originally developed by US Synthetic in the early 1990s. This type of cutter involves pressing a solid polycrystalline diamond disc, which is then fully leached to remove substantially all of the interstitial cobalt. This disc is

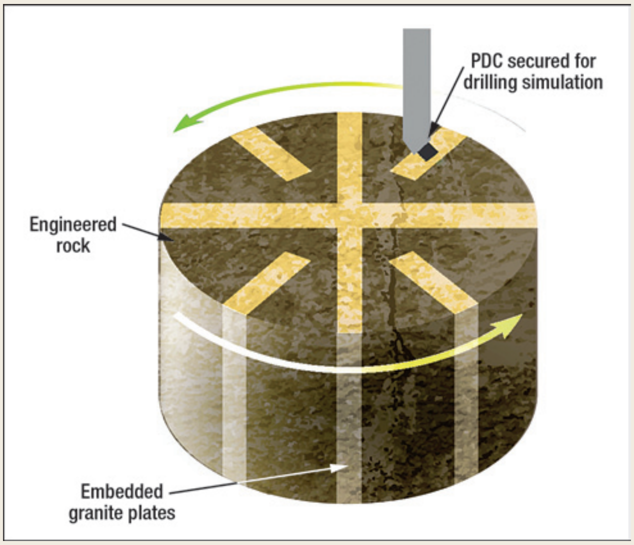

**Fig. 2.** Varel's Bimodal Abrasive Rock Test uses an engineered rock sample to combine abrasion and impact testing. This simulates drilling conditions more accurately and speeds testing time compared with traditional abrasion testing.

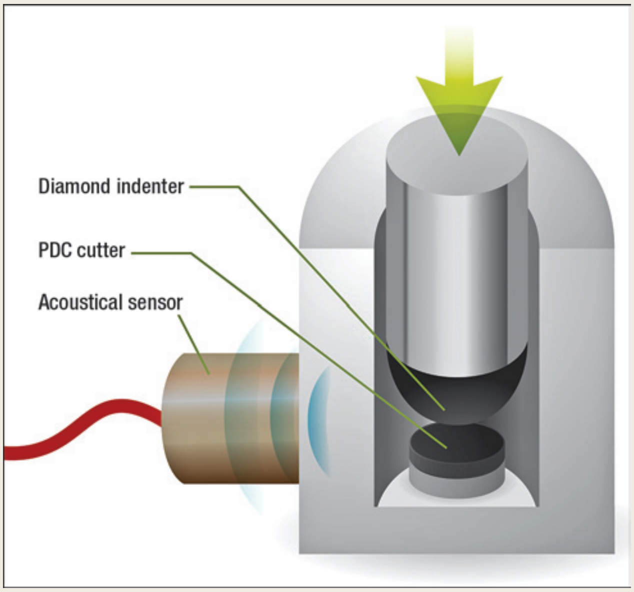

**Fig. 3.** Varel's Acoustical Emissions Toughness Test measures micro-cracking to quantify the strength of diamond-to-diamond bonds in the PDC cutter's diamond table.

then loaded into another pressing cell with a tungsten carbide substrate. The combination is put back through an HPHT press cycle to attach the leached disc to the substrate to yield a high-thermal-stability PDC cutter. Challenges to this method include the potential for excessive sweep of cobalt into the diamond disc during the second press cycle, instances of weak bonding between the diamond disc and the substrate and low production yields in the overall manufacturing process.

Another area being explored by diamond makers is the use of higher pressures and temperatures, which can be used to form catalyst-free diamond-to-diamond bonds. As Fig. 1 shows, the pressures and temperatures required to synthesize diamond in a catalyst-free environment are roughly 1½ times typical PDC manufacturing parameters.

This approach poses several challenges. Presses capable of delivering the range of pressure and temperature required are very large. They typically can only hold a very small pressing cell. The lives of the expensive anvils used at these elevated energy levels are very short. Finally, it is extremely difficult to attach these pure diamond constructs to a substrate for use in drilling.

Another avenue of diamond research involves diamond manufactured using carbon vapor deposition (CVD). This technology uses low temperatures in vacuum environments to layer vaporized carbon onto a substrate. Under the proper conditions, a diamond film is formed in minute, micron-thick layers. This technology has shown great promise in the areas of optics and electronics but as yet has not proven to be effective in high-load wear environments like drilling. One potential use proposed for CVD diamond is as a back-filling material into the face of a leached PDC diamond layer to plug the interstitial voids left by the leaching process.

A final area of diamond research revolves around the substitution of silicon carbide for cobalt containing tungsten carbide, or the use of silicon carbide intermixed with the polycrystalline grit prior to the pressing cycle. In either case, the goal is to have the silicon carbide act as the catalyst for the diamond-to-diamond bonding. The advantage is that the coefficient of thermal expansion of silicon carbide is nearly identical to that of diamond. The silicon carbide that remains in the interstitial areas of the polycrystalline diamond table expands less than cobalt under frictional heating and, therefore, makes for a more thermally stable diamond table. The disadvantage here is that silicon carbide is a less effective catalyst than cobalt and produces a weaker bond to the substrate.

**Testing.** Advancements in PDC cutter technology are driving the development of new testing techniques for super-hard materials. A newly developed non-destructive testing method includes the use of X-ray radioscopy. In this case, the investigative energy is put into the face or across the diamond table to obtain more finely detailed inner views of the diamond table than are obtainable through the traditional C-scan method. Viewing through the side of the diamond table allows a quantification of the depth of various gradations within the diamond table, such as leach depth. It also allows for a determination of the quality of the diamond-to-substrate interface.

The primary drawback of traditional abrasion testing is the amount of time it requires. As cutters have improved, this time requirement has become even greater. The primary drawbacks of traditional drop hammer tests for impact toughness are the substantial numbers of cutters that must be tested to get a statistically reliable analysis and the amount of time required to run an adequate battery of tests.

Two new methods have been developed to address these issues. The first is Varel's proprietary Bimodal Abrasive Rock Test (BART). This test uses an engineered rock sample that incorporates highly abrasive cement cast around upright slabs of high-compressive-strength granite. When single PDC cutter tests are run in a vertical boring mill, this rock construction more accurately simulates actual drilling conditions, with repeated transitions from the abrasive cement to the high-compressive-strength granite, Fig. 2. In this manner, the traditional abrasion test has been upgraded to incorporate a high-impact component. This combination speeds the testing by more rapidly breaking down the PDC cutter while yielding a more complete qualification and quantification of a specific cutter's applicability to transition drilling.

The second newly developed method, also by Varel, is Acoustical Emissions Toughness Testing (AETT). This testing technology uses a domed PDC indenter to load the face of a PDC shear cutter, Fig. 3. The test cell is instrumented with a highly sensitive acoustical sensor. As the force applied to the PDC diamond layer is increased, it begins to experience micro-cracking. The acoustical sensor detects the micro-cracking events, which are then recorded on a hard drive and displayed on a monitor. The test accurately quantifies the strength of the diamond-to-diamond bonds within the diamond table. Different types and grades of PDC cutters can be compared according to their resistance to load-induced micro-cracking to yield a highly predictive valuation of impact strength. In addition, the test method has application as a process control/quality control instrument for PDC cutter manufacturers.

When used in combination, these two testing regimens promise to significantly accelerate cutter development by speeding the qualification of new cutters and by providing more accurate quantification of prototype cutter attributes.

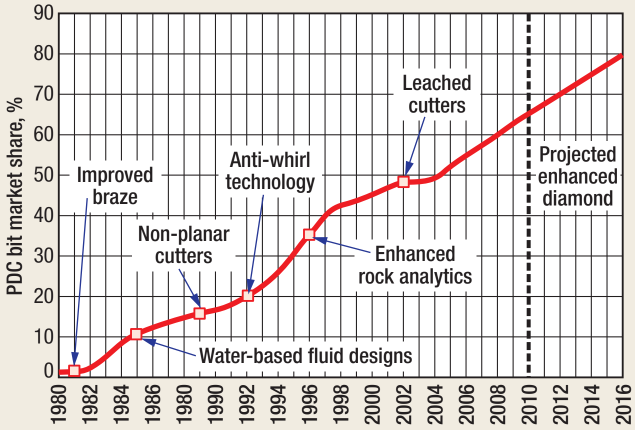

**Fig. 4.** PDC bit market adoption “S” curve, from 1980 to projected 2016. Courtesy of Varel International and Spears & Associates.

## PDC TECHNOLOGY MATURATION

Three decades of development of PDC bits as a commercial alternative to traditional roller-cone bits have been marked by waves of technological improvement accompanied by adoption in new applications. The cycle of improvement can be plotted as a typical technology innovation “S” curve, Fig. 4. This curve shows remarkable growth in PDC market share since 1982, when PDC bits were used for only 2% of footage drilled worldwide, compared with 98% for roller-cone bits.

All aspects of PDC cutter and bit technology have matured, including materials, geometry, erosion resistance, vibration control, torque control, hydraulics and cleaning, casting integrity, diamond formulations and diamond table pressing and treatments. During the same 30-year period, roller-cone drill bits have also improved significantly. The roller cone bit of today performs 1½ to five times better than the equivalent bit of 1980. This has been the result of improved seal and compensation systems, advanced insert designs, improved bit body hydraulics and better hardfacing and hard-metal formulations. Ironically, one of the contributors to improved roller-cone bit life has been the incorporation of diamond-enhanced inserts (dome-shaped PDC cutters) in roller-cone bit gauge and cone cutting structures.

Even with these improvements, the roller-cone side of the industry has been fighting a losing battle against market encroachment by PDC bits. The improvements in roller-cone technology have not kept up with the improvements in PDCs. Furthermore, these improvements in fact have resulted in fewer roller-cone bits being required even in applications that are still best drilled with roller-cones.

New advancements in PDC technology promise to assail many of the remaining applications where roller-cone bits are still preferred. These applications include hard rock zones such as chert, pyrite, siderite, granite and dense dolomite. In addition, highly abrasive rock such as sharp sands and quartzite are candidate targets. Successful encroachment into these applications could push roller-cone bits to a “specialty” categorization in specific areas including shallow, low-cost land operations, large-diameter (26-in. to 36-in.) offshore top-hole applications, and reaming, cleanup, junk and rat-hole runs.

The drivers for this encroachment are the same as they have been since the earliest applications of PDC: the attraction of a lack of moving parts and of seals, the erosion resistance of tungsten carbide matrix bodies, the ability to handle high rotation speeds, the promise of high rates of penetration and the ability to rapidly manufacture specialty gauge and cutting structure configurations.

As this marginalization of roller cone bits continues, it would seem reasonable to estimate a “footage drilled” split of at least 80% PDC to 20% roller-cone over the next five to 10 years. In the extreme, if diamond materials and cutter geometry developments can take PDC fully into the heart of the remaining applications for roller-cone bits, then the split could exceed 90% to 10% within the next 10 years. **WO**

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### BIBLIOGRAPHY

For the complete bibliography of Parts 1–3 of this article series, visit www.worldoil.com.

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