Aligned Materials and Design Development of High ROP Drill Bits
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Abstract
At their advent, PDC bits were aimed at soft formation, fast drilling applications. However, as PDCs have come to dominate market share over roller cones, PDC bit development has shifted focus toward other goals such as durability and longevity which is often in conflict with high ROP. Returning focus to aggressive, high ROP drilling applications has required development of materials, design and manufacturing processes in alignment with that goal set.

A cross-functional team was assembled to understand and focus on the high ROP concerns of the end customer and was tasked to develop a PDC bit platform aligned with these goals. This paper discusses general and application specific challenges posed by high ROP drilling applications and how they have been addressed by the aligned development of a new system of materials, design, and manufacturing processes used in PDC drill bits. Formation to bit interaction simulations and computational fluid dynamic modeling analysis are presented in support of the development hypotheses. Field results from case studies and broad field data analysis summarizing the results of extensive testing are presented as well.

Driving ROP beyond the ceilings observed in many extreme ROP applications requires that energy be efficiently transferred not just to the bit, but focused on the cutters. To achieve this, an essential change to the base material of the bit body was made, exposing drastically new avenues – and hurdles – for design and manufacturing. However, the simulation and field results presented confirm that the new system is able to consistently achieve the goal set in high ROP applications.

Introduction
Since the introduction of PDC bits into oil and gas drilling, bit engineering challenges have regularly shifted back and forth between materials development and advancing design around the expanding material capabilities. In PDC bits, however, failure to address manufacturing challenges, or at best addressing them in isolation from materials and design development, has often stymied the use of otherwise superior materials and designs. The most widespread case is the preference of bit manufacturers toward bit bodies cast from brittle and expensive tungsten carbide “matrix” rather than machined from much tougher steel.

Drilling hydraulics create a very hostile and erosive environment, and nowhere is this more extreme than the bit which is subjected to an extraordinary amount of erosive hydraulic energy. In this environment bare steel alone cannot maintain the structural integrity to support the cutters due to the erosion. While advanced hard surfacing materials, which are in fact superior to tungsten carbide matrix powders used in bit bodies, are readily available to overlay onto steel, the application process is difficult, manual, and hence imperfect. In contrast, though, design capabilities in steel are much more robust.

An operator active in drilling the Marcellus shale in the northeast U.S. posed a challenge to build a bit with all of the performance and design advantages afforded by steel without the traditionally associated drawbacks. Observing manufacturing capabilities as the major hurdle, an ongoing project was initiated to develop a platform addressing materials and design in concert to facilitate the manufacture of steel body PDC bits to the highest quality standards in the industry. A cross functional team comprised of manufacturing and hard surfacing experts, material scientists, PDC design engineers, and drilling applications engineers was assembled to focus on the concerns of the end customer.

PDC Design & Manufacture: History and Drivers
PDC drill bits are composed of two main components: diamond cutters and a body. The predominant view in the industry is that cutters are the most important part of the PDC bit, as they are required to engage the formation and maintain their geometrical properties long enough for shear drilling to be economical. The bit body, then, is necessary only in order to hold
the cutters in their arranged layout and to convey mechanical and hydraulic power to remove the rock in their path (Deen). By jointly developing the cutting structure and bit body tasked with maintaining it, PDC bits have drastically improved drilling economics in the industry. (Turner)

All PDC bits are manufactured from steel or tungsten carbide powder infiltrated with a binder alloy (matrix), both of which have very different properties. Traditionally, matrix PDCs are believed to have superior fluid erosion resistance. Conversely, while steel is vastly inferior in terms of resistance to fluid erosion, it is significantly superior in strength, a fact that is unfortunately contrary to the belief of many operators. These properties alone tend to require matrix bits to have shorter, thicker blades versus taller, thinner blades on steel PDCs. A visual indication of this difference is apparent in most designs with the different base materials (Figures 1a & 1b). The difference in open face volume (the volumetric fraction of the bit face that is left open for cuttings evacuation) has led some to the conclusion that matrix bits are “best suited to long intervals of relatively slow drilling … [and] steel bodied bits are best suited to applications where the open face volume can contribute to high penetration rates.” (Taylor)

As detailed by Taylor, et. al., extensive attempts have been made to enhance both base materials used in PDC bit bodies either by reinforcing matrix to bolster strength, or cladding steel to improve erosion resistance. Unfortunately, advancements made, both in drill bits and in other industries using the same materials, have seldom been fully utilized due to failure to develop design and manufacturing techniques and processes in parallel. By carrying out research and development on materials, their application, and designing for use of the same, performance advances predicted decades ago have been made.

The primary challenge for design engineers was to identify and overcome the ROP restrictions inherent to existing bit designs. In high ROP applications, there was an apparent ceiling on ROP which was independent of cutter count. In spite of several attempts at reducing cutter density, the most common design adjustment by which ROP is manipulated, the expected gains were not realized. It was hypothesized that non-cutter blade to formation contact was creating an unwanted bearing surface on the bit which absorbed WOB rather than using it constructively to fail the rock. Development was needed to improve the potential for the cutters to efficiently engage the rock.

PDC bits are often designed with cutter exposure in mind. Cutter exposure is a measurement of how far the cutter face extends from the blade top surface (Figure 2). This is also the geometrical maximum depth that the cutter can engage the rock without the blade top becoming a load bearing surface. At this maximum engagement, additional WOB becomes ineffective in increasing cutter engagement, and therefore ROP. Cutter exposure must also be balanced with cutter retention. While too low exposure limits ROP, too high exposure reduces the brazing surface area and strength which puts the cutter at risk of being lost from the bit altogether.

Exposure, though, does not only exist in the dimensions depicted in Figure 2. As the bit rotates in the hole it is also advancing in a helical trajectory, creating an ROP slope (Figure 3). The ROP slope is a function of the rate of forward advancement of the cutter along the cutting path (given by RPM and radial position along the bit profile) and the rate of advancement in the drilling direction (given by ROP.) Because of this slope, it is not only possible that bit ROP can be limited by cutter exposure at the front of the blade, but also by the effective exposure of the back of the blade to the ROP slope. Both needed to be addressed.

Realizing Material Strengths through Design

Simulations of standard PDC bit designs confirmed that when ROP reaches a certain point, weight transmission to the bit was largely inefficient in drilling new hole because a considerable portion of the blades were simultaneously being buried in the formation (Figure 4). Therefore, energy that could be directed to drilling was being wasted on unproductive blade surfaces whose sole function ostensibly is to hold the cutters in place rather than serve as a de facto bearing surface. In so doing, the blades and bit body consume hole-producing weight that otherwise could be transmitted to the cutters.

The wider nature of matrix blades, necessitated by the inherent weaknesses of the material, can cause the back of the blade to become an effective exposure limitation (Figure 5a). Thinning and removing this performance impeding part of the blade structure requires the toughness of steel (Figure 5b). Further, the manual process of cladding the bit can cause an unwanted and difficult to control buildup of tungsten carbide on flat surfaces. The design feature of adding a meaningful taper to the back of the blade top adds considerable accuracy and quality control of the hard facing thickness at the front of the blade. The new platform creates PDC bits without the limitations of material weaknesses and instead strategically aligns the individual components to seamlessly capitalize on their individual strengths.

The thinner blades, that nonetheless are roughly four times stronger than those of conventional matrix PDC bit designs, combined with the novel tapered geometry fully addresses exposure limitations at the back of the blades. These thinner, yet more durable, blades clear the way for steel body PDC bits to be designed to maximize the ROP potential from every size of cutter. The ability to significantly raise the traditional ROP ceiling associated with cutter size reduces conflicting durability tradeoffs based on cutter size and count. Optimizing the exposure of any cutter size for high-speed drilling allows up to a 40% improvement in ROP response to WOB over a standard PDC bit.

Consistent delivery of mechanic specific energy (MSE) into the rock is the hallmark of drilling efficiency. The capacity to divert more energy into actually failing rock is a function of the uniquely streamlined blade configuration, which in a sweeping departure from traditional PDC bit designs, features a minimalist approach to supporting the cutters, enable by stronger and more specialized materials. In other words, the smaller profile diverts energy directly to the diamond cutting surfaces and into the formation.
Hand-in-hand with the increased exposure, the novel layout enlarges the junk slot area up to 20% compared to conventional steel-body PDC bits and up to 40% larger than their matrix counterparts. The slimmed down blade configuration, along with enlarging open face volume, optimizes hydraulics for highly effective hole cleaning even in extreme gumbo and swelling shale environments. The geometrical configuration allowing increased exposure can also prevent micro balling that can quickly build up on the tops of blades contacting the formation (Figure 6). Essentially, the drilling fluid flows more efficiently through the cutters and with the increased exposure maintains a cleaner hole bottom for continuous cuttings evacuation.

The major operator had used the previous generation Ulterra PDC bit to drill more than 80% of the curve and laterals in its Marcellus drilling campaign where it generated top-end instantaneous ROP of up to 320 ft/hr while rotating. While delivering impressive drilling rates, the earlier PDC bit type had reached a performance ceiling, prompting the operator to request a directional bit that could increase instantaneous ROP to around 500 ft/hr. This request was complicated by the requirement to also effectively build the curve and hold azimuth during rotation to reduce walk tendencies in the longer laterals. Specifically, the prototypical directional bit would couple high instantaneous drilling rates with the capacity to build angle and exhibit superb tracking and response to steering inputs in the horizontal interval thereby increasing overall ROP and footage drilled.

The operator request spurred the aforementioned wholesale reevaluation of conventional steel body PDC bit design protocol, specifically for the longer laterals intrinsic of the Marcellus and other shale plays. The step-change amounted to overall rates of penetration (ROP) roughly 33% faster than standard PDC bits (Figure 7). The new blade top geometry allowed the simultaneous increase of both potential top-end ROP and durability. Despite making the switch to a 13mm cutter from a 16mm cutter, cutter exposure was still increased by 66%. This additional exposure drastically increased the potential ROP of the bit while the additional cutters increased durability of the shoulder, ensuring the bit would maintain the additional ROP throughout the run. This is reflected in comparable per-run footage increases averaging 36%. Accordingly, combining longer bit life and higher ROP with exceptional tool face control has translated to estimated cost-per-foot savings amounting to nearly $57,000 per run, based on contemporary Marcellus spread rates.

An examination of the bit record dataset over a one-year period showed the operator drilling a cumulative 182,580 ft of Marcellus curve and lateral sections with earlier generation PDC bits in 2,352 total hours at an average ROP of 76 ft/hr, thereby accumulating an aggregate 1,863 ft over every 24-hr drilling period. By comparison, the later change to the new generation PDC bit resulted in the drilling of 92,929 ft of curve and lateral intervals in 990.7 hours for an average penetration rate of 93.8 ft/hr. Consequently, the new design allowed the operator to drill an average 2,251 ft of new formation over the average 24 hr period.

Cumulatively, the new PDC bit design has increased average per run footage drilled 36% to 1,311 ft. When compared to offsets employing traditional PDC bits, the increased ROP with the new generation design, in turn resulted in 52% more daily footage drilled. Assuming a $48,000 daily spread rate, the improved drilling efficiencies saved the operator $56,976/run for an aggregate savings of just over $1.08 million.

**Marcellus Shale Case Study**

Generally, the curve and lateral sections of Pennsylvania Marcellus Shale horizontal wells penetrate the Tully limestone and the underlying Hamilton, Burkett and Upper Marcellus shales that overlay the targeted Lower Marcellus pay zone. Occasionally, well trajectories require drilling troublesome Cherry Valley limestone stringers while building the curve, or drilling the lateral where historically PDC bits have sustained severe impact damage to the point of coring out. Further, operators frequently must contend with the extremely ratty transition from the interbedded chert stringers in the extremely hard Onondaga limestone below the Marcellus, which has proven equally detrimental to PDC bit longevity and performance. Representative Marcellus wells are batch drilled on pads averaging four to six wells with programmed laterals that have been extended sequentially from 4,000 ft. to 7,000 ft. Typical curve build rates range from 8°/100 ft. to 10°/100 ft. with turns of 60° to 120° commonplace in today’s wells. Furthermore, owing to the melding of environmental limitations and down hole characteristics, Marcellus wells generally are drilled with invert emulsion synthetic-based mud (SBM) with densities ranging between 11.7 lb/gal and 13 lb/gal.

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**Conclusions**

The performance improvements observed in the Marcellus Shale application has since proven to be typical of many fast drilling applications when the discussed technology has been applied. Since then, the entire portfolio of project developments has been honed, packaged for commercial release, and now implemented in over 70 unique designs, spanning 20 bit diameter sizes and 12 combinations of blade count and cutter size. These designs have accumulated over 1000 runs on the platform, and millions of feet drilled, most often achieving performance improvements over traditional technology.

Based on these heavily one-sided results, the authors are confident that materials selection should not be considered a foregone conclusion in PDC bit design. In contrast, design and materials selections should be optimized to each other with consideration to leveraging the strengths and avoiding the weaknesses of the materials selected. In high ROP applications,
such as the Marcellus Shale, performance, and thus economic improvements can be achieved through application of bits of tailored material and design optimization.

**Nomenclature**

- **PDC** = Polycrystalline Diamond Compact [Drill Bit]
- **ROP** = Rate of Penetration (or penetration rate)
- **JSA** = Junk Slot Area
- **OFV** = Open Face Volume (fraction of the bit face volume left open for cuttings evacuation)
- **DOC** = Depth of Cut
- **LCM** = Lost Circulation Material
- **CFD** = Computational Fluid Dynamics
- **QC** = Quality Control

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**Works Cited**


Appendix

Figure 1a: PDC bit with conventional matrix blades

Figure 1b: PDC bit with new-style steel blades

Figure 2: Cutter exposure and maximum engagement

Figure 3: Cutter advancement as RPM and ROP create and ROP slope.
Figure 4: Bit body/formation interaction simulation showing contact area in red.

Figure 5a and 5b: old blade geometry interfering with ROP slope and new geometry.
Figure 6: CFD illustration showing cleaning of blade tops.

Figure 7: Test vs. offset footage and ROP.