PROCEEDINGS, Thirty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 1-3, 2010
SGP-TR-188

SUPER-HARD, THICK, SHAPED PDC CUTTERS FOR HARD ROCK DRILLING: DEVELOPMENT AND TEST RESULTS

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ABSTRACT

Throughout the history of oilfield drilling, workers have tried to improve drill bit mechanical efficiency. Various cutting theories, designs and materials have been implemented to increase Rate of Penetration (ROP), wear resistance and overall bit life. The advent of the Polycrystalline Diamond Compact (PDC) cutter in the mid 1970's started the gradual movement away from the roller cone bit to the shear cutter bit. The geometry of the PDC cutter changed the cutting mechanics from a point load or crushing of the rock to a transverse shearing motion. PDC bits have a number of advantages over roller cone bits in some environments and in many applications significantly outperform them. However PDC bits in geothermal drilling remains a field of relatively limited experience and is an area where PDC fixed cutter bits under-perform compared to roller cone bits. A new, hard, thick, shaped Stinger™ PDC has been invented that aims to provide a link between crushing and shearing of rock to improve both ROP and overall cutter life. This paper describes the testing of such a cutter and preliminary work on Stinger-populated drill bits aimed to enhance ROP in geothermal and EGS applications.

Background

The relatively poor performance of PDC bits in harder formations has been discussed by various authors since the inception of the PDC in the 1970's. Despite the fact that PDC bits tend to start drilling at higher ROP than roller cone or impreg bits, PDC's have been observed to reduce ROP quickly leading to increased Weight On Bit (WOB) and ultimately the pulling of the bit. Steady state testing of early drag bits (Appl *et.al*, 1962) and PDC cutters (Langveld, 1992) showed that both cutters and bits should last much longer than had been observed in the field.
The difficulty of obtaining long bit life in hard rock was discussed by Feenstra (1988) where temperature limitations and impact resistance of the PDC's were highlighted as areas for improvement.
Glowka (1989) stated that wear flats on diamonds require additional force to make a cut since the WOB has to crush additional rock to achieve penetration. The frictional energy generated by the higher WOB on dulled cutters heats up the cutter. This leads to thermal damage and delamination of the PDC and ultimately limits bit performance.
Brett *et.al*,(1990), described bit whirl as the cause of cutter chipping and failure, where chaotic bit motion, due at least in part to unbalanced cutter forces (Weaver and Clayton, 1993), leads to whirling of the bit. Bit whirl resulted in off rotation axis motion and cutters engaging the formation in directions other than perpendicular to their intended direction. Subsequent work by many manufacturers resulted in "Anti-Whirl" bits with low friction gauge, as described by Warren *et.al*, (1990) and Clegg (1992).
Once the bit balance and whirl issues appeared solved, bit manufacturers set about improving the bit longevity by increasing the diamond volume on a bit through thicker diamond, increased cutter and blade count, increased back-rake, and use of smaller cutters (Sinor *et.al*, 1998; Mensa-Wilmot and Calhoun, 2000). This tactic, despite generally making the bits drill slower, did appear to make the bits last longer.
Discussion of drill string effects that include vibration axially, laterally and torsionally by Langveld (1992) and Warren and Sinor (1994) showed that each of these modes of vibration could significantly damage cutters and the bit as a whole. This work has led to the modeling of the bit and BHA as a single system (Barton *et.al* 2007) in an effort to fully understand the various forces that affect the ROP and overall bit performance during the drilling process.
Much work has been done on improving diamond formulations, thermal stability, interface strength and cutter geometry (to name a few parameters) with the overall goal of increasing impact and abrasion resistance. Complex engineered geometries or non-planar interfaces have been applied to the tungsten carbide (WC) substrate (Mensa-Wilmot and Ramirez, 1999; Mensa-Wilmot and Penrose2003) to help reduce stresses as a result of the sintering process, and ultimately reduce chipping and spalling. This in

turn led to improved wear life as the thickness of the diamond table could be increased.

Improvements have also been made in the preparation, diamond grit quality and sizing, press engineering, cell design and sintering process, all of which contribute to the final quality of the diamond and its abrasion and wear resistance. Perhaps the most significant recent advance in the abrasion resistance of the PDC has been the invention of the leached PDC (Schell *et.al*, 2003). Leaching of the diamond (which is typically applied to premium quality cutters only) has been shown to improve the overall abrasion/heat resistance of the PDC. The leaching process is one where interstitial cobalt is removed from approximately the outer 100µm of the diamond surface to reduce the effect of the differential thermal expansion between diamond and cobalt. Cobalt is also thought to catalyze the reversion of diamond to graphite at high temperatures. Improvements to the PDC such as leaching are generally known in the industry but specific details are closely held proprietary technologies that have been the subject of patent litigation.

All of the above work has recognized to some degree that imbalance forces (that are largely unknown and unrecorded) remain in the downhole drilling environment. These forces compromise the PDC by chipping the edges and dulling the bit. While improvements to the quality and durability of the PDC's have no doubt been achieved in recent years, the durability of the PDC is ultimately in question. This paper intends to address the problem from a different direction; one where the PDC is inherently designed for strength and durability.

The Stinger Cutter

Improved press technology by our company has led to larger cell size and capacity as well as ability to use higher pressures and temperatures during the sintering process. The larger cell allows for larger parts or for more parts per run while still providing adequate clearance between parts. Thus the Stinger can be made in reasonable quantities and with a thicker diamond table than most manufacturers are able to make consistently. The shape of the Stinger and cross-section of the part is shown in Figure 1.

Figure 1: Stinger PDC cutter, showing shape and thickness of diamond table.

The black conical shaped portion is the polycrystalline diamond, and the rounded dome is the tungsten carbide – cobalt substrate. The included angle of the diamond is approximately 85 degrees and the radius of the tip is 0.090". Other angles and radii were tested, and selection of the appropriate geometry for an application depends on the mechanical mode (penetrating or shearing) in which the cutter is to be used. Figure 2 shows a cross-section of a conventional PDC shear cutter featuring a non-planar diamond-carbide interface.

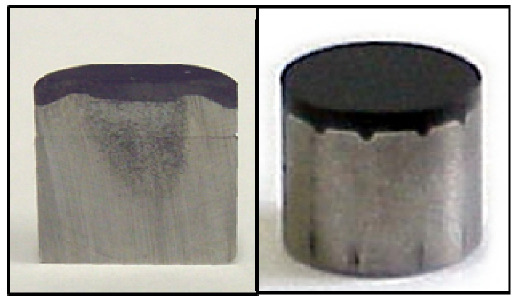

Figure 2: Conventional shear PDC cutter.

The angle of attack at which the Stinger contacts the rock was also considered. The Stinger orientation in a bit will not be the same as with the shear PDC since the cutting mode is more plowing and crushing rather than shearing. The orientation of the Stinger is chosen to take advantage of its inherent strength by focusing the resultant cutter force into axial compression at the tip. In a bit application where both vertical down force (weight on bit or WOB) and rotation around the vertical axis are at play, the Stinger must be oriented with the tip pointing down and forward in the direction of rotation. The forward tilt of the axis was chosen to fall in the middle of the range expected when drilling hard rock at representative drilling rates. Laboratory tests on a Vertical Turret Lathe (VTL) measuring the force components while aggressively cutting granite at depths up to 0.150" formed the basis for this decision. An angle of 17° from vertical best satisfied the criteria for strength and cutting effectiveness. Drop testing was also used to measure the energy required to fail the cutter at angles of up to 30 degrees off-axis. Since the impact strength held steady up to 17 degrees, the 17 degree mounting used on bits should be load-tolerant for resultant angles to ~30 degrees.

Impact resistance

The impact resistance of Stinger and shear cutters was tested using a laboratory drop test machine. Drop tests were conducted on the Stinger PDC at impact angles between 17 degrees and vertical.

Conventional PDC shear cutters were oriented at 10 degrees from the plane of the face . The testing showed that the Stinger PDC geometry had 4 to 9 times the impact resistance of a comparable sized shear cutter when dropped onto a WC target. A plot of this data is shown in Figure 3. These results suggest that the Stinger should be significantly more resilient to impact loading observed on a bit in the downhole environment.

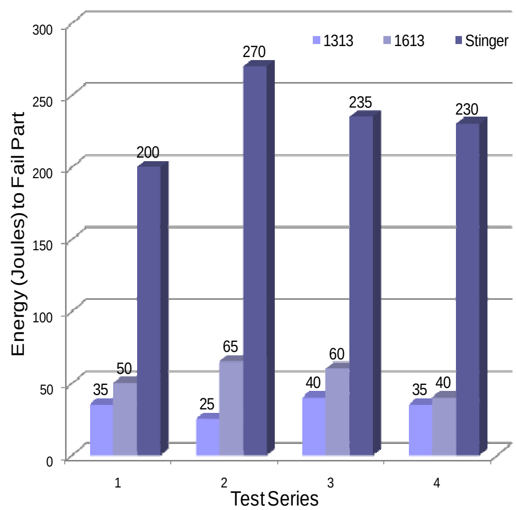

Figure 3: Plot of relative impact energy required to fail both Stinger and conventional shear PDC cutters.

Stinger PDC's were also impact tested against round top inserts such as are commonly employed in roller cone bits. Results from the round top inserts impacting a WC target are shown Figure 4. The round top cutter created an impact deformation volume of about 80% of the deformation volume created by the Stinger, while the impact depth caused by the round top was less than 33% than that of the Stinger. These results suggest that the Stinger should be a more aggressive tool with which to disintegrate rock formations.

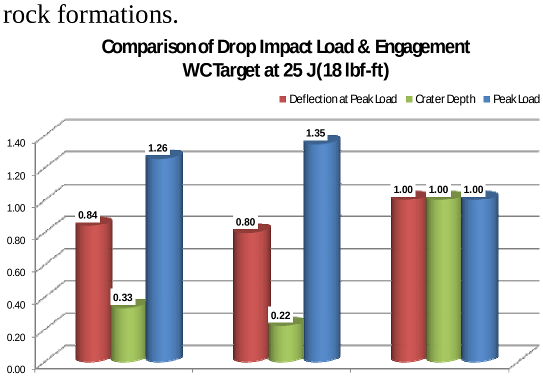

Figure 4: Normalized values of impact energy and target deformation for Stinger cutters vs. conventional round top inserts.

VTL Testing

The common industry method of conducting accelerated wear or abrasion tests on PDC cutters is to cut a cylindrical log of rock material on a specially instrumented lathe. In this case, a Vertical Turret Lathe was used, rotating a slab of Sierra White Granite having compressive strength of approximately 24k psi. A fixture holds the PDC and allows the cutter to be brought against the rotating, unconfined, rock surface. The Computer Numerical Control (CNC) device controls depth of cut, rotary speed, linear speed and feed rate. The tests can be done wet or dry to vary the thermal stress imparted to the cutter. Wet testing may best simulate the presence of mud in the borehole by cooling the PDC and removing compromised rock material as well as reducing dust. Dry testing eliminates the dominant mode of cooling the PDC and accelerates wear and cutter burnout.

Wear resistance.

Initial testing of the Stinger on the VTL was carried out against both premium (surface-leached) and lower grade cutters. Each cutter in the initial test phase was subjected to 50 passes at 0.050" depth of cut, 0.300" in feed and 25 RPM. Wear on the cutters following this test process is shown in Figure 5, Figure 6 and Figure 7. These results indicated that additional testing was necessary to understand the cutting mechanism and factors affecting the longevity of this cutter.

Figure 5 Results of initial VTL testing on low grade PDC shear cutters. Test included 50 passes, 0.050" depth of cut, 0.300" in- feed rate and 25 RPM.

Figure 6: Results of initial VTL testing on premium (surface-leached) PDC shear cutter.

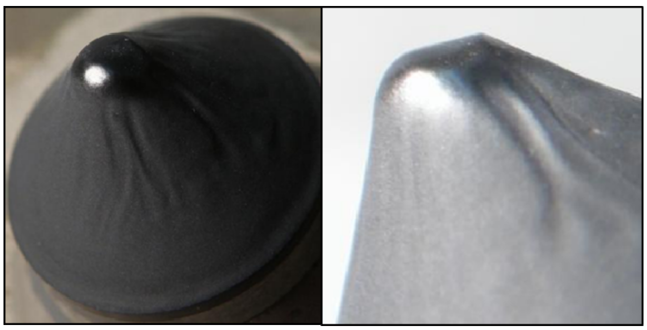

Figure 7: Results of initial VTL testing on non-leached Stinger PDC cutter.

Average forces

The VTL machine was also fitted with a 3-axis load cell which allows for forces to be measured and recorded. Force data was recorded over 50 passes for the Stinger, in-house 13mm shear cutter and cutters from five different manufacturers. Figure 8 shows that the average vertical force increased as the number of passes across the rock increased and the cutter became dull. New, sharp shear cutters started the test with low down force (<500lbs for all cutters on the first pass) in order to achieve the 0.050" depth of cut. However it is clearly observed that after only five passes, all of the shear cutters required down force which was higher than that for the Stinger. The Stinger, while starting testing in a 'duller' condition (due to the tip radius) than the shear cutter was shown not to wear as quickly as the shear cutter. Subsequent passes serve to further dull the shear cutters and result in higher down forces required to maintain cut depth.

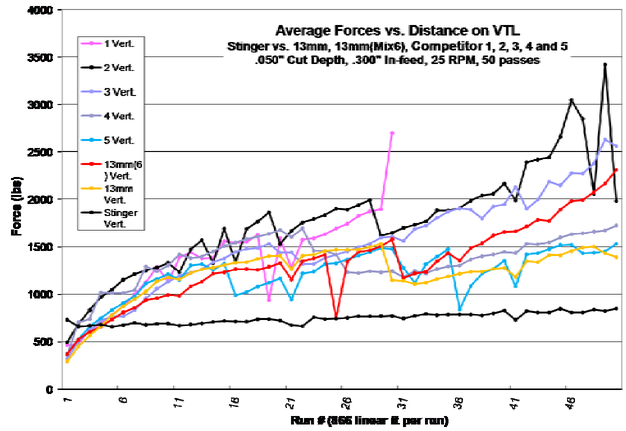

Figure 8: Average vertical forces recorded over 50 passes on the VTL for shear and Stinger cutters.

Generally, the shear cutters show a tendency to gradually dull, and the down-force required to maintain depth of cut increases by 3 to5 times over the 50 pass test. Large changes in the force on the shear cutters are attributed to chipping of the PDC, which results in a short-lived sharpening of the cutting edge. The average force on the Stinger PDC did not increase by the same relative amount as those of the shear cutters and ended the test about 30% higher than at the start point. This result could indicate that in a down hole situation cutter dulling may be reduced, allowing ROP to be maintained without increasing WOB as the bit run progresses. It is often observed in the field that as the PDC cutters dull, WOB must be increased to maintain ROP. This tends to result in a spiral of cause and effect, leading to cutter failure and / or pulling of the bit for low ROP.

<u>Cutter Life Testing</u>

Further tests were undertaken to observe cutter life over extended testing.

Wet Testing

Wet VTL testing was carried out on shear cutters and Stinger cutters. Testing was similar to previous tests, with the following parameters: 0.300" in-feed, 0.050" depth of cut, and a constant 270 surface feet per minute. New 13mm shear cutters were set in the fixture with typical 15° back rake angle. Stinger cutters were fixtured with 17° forward rake angle. Photos of the shear cutter following 75 passes across the granite (62,635 linear feet travelled) are presented in Figure 9.

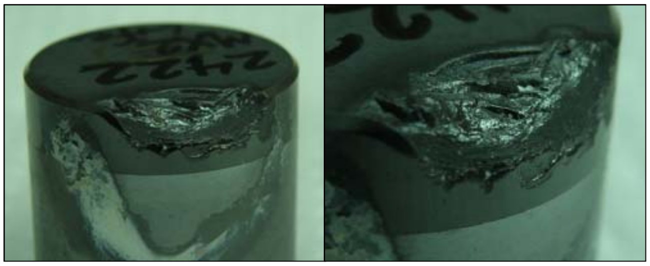

Figure 9: Shear PDC cutter following 75 passes on the VTL, 62,635 linear feet traveled.

Initial failure of the shear cutter first occurred at pass 40, where a large piece of the PDC material chipped off. The test was continued until pass 75 at which point the cutter had failed. Vertical force required to cut had increased 4x during the test, while drag forces increased 3x during the test. Photos of the Stinger cutter following 140 passes (116,920 linear feet traveled) are presented in Figure 10.

Figure 10: Stinger PDC cutter following 140 passes on the VTL.

The wet testing of the Stinger, could have continued farther was stopped at 140 passes due to excessive consumption of the granite. The vertical and drag forces applied to the shear and Stinger cutters as the test progressed are shown Figure 11. Vertical forces on the Stinger increased 50% to 100% during the test while drag forces remained constant over the 140 passes. The wet test showed that the Stinger was capable of withstanding 2 to3 times the linear distance during abrasion testing. Drag force data would suggest that in a downhole situation, as a shear cutter wear increases, resulting bit torque would also increase. Correspondingly, WOB would also be increased to maintain ROP.

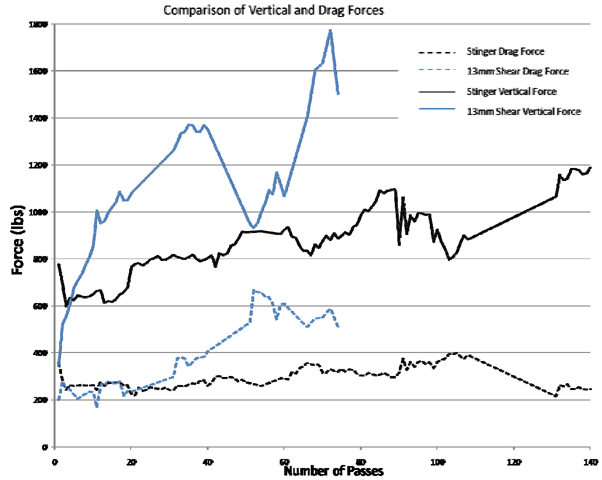

Figure 11: Comparison of vertical and drag forces against number of passes on the VTL.

Hot Testing:

Cooling the PDCs during VTL testing allows the cutter to dissipate heat away from the cutting surface to the fluid, substantially prolonging the length of the test prior to burnout and failure. Dry or hot testing requires the cutter to dissipate the heat by conduction through itself to the WC substrate and typically leads quickly to mechanical breakdown, oxidation, and graphitization of the diamond. The laboratory dry or hot test better simulates conditions of deep, hot, and abrasive drilling such as may be encountered in many geothermal applications.

The VTL hot test followed these parameters: constant 270 surface ft per minute, 0.050” depth of cut and 0.200” in-feed. As per previous tests, PDCs were oriented at a17° rake angle for the stingers and a 15° back rake angle for the shear cutters. The test was continued with no coolant until cutter burnout, indicated by development of a black graphite line on the granite block, usually accompanied by dramatic red heating of the cutter to red glow and sparking

The comparison test was conducted using 13mm non-leached and deep-leached PDC shear cutters and Stinger PDC non-leached and deep-leached. Results from the tests are shown Table 1. Stinger cutters demonstrate the ability to cut approx 12 times the linear footage of the shear cutters. The forces required to maintain the 0.050” depth of cut were recorded and are shown graphically in Figure 12. As observed in previous tests, the shear cutter started the test with lower force requirement but as the cutter dulled, the force multiplied 3-4 times prior to burn out. The Stinger cutter forces increased gradually until pass 40, where failure started to occur.

Table 1: Results of VTL hot tests, comparing number of passes and linear distances traveled between the cutter types.

PDC Cutter Type	Number of Passes	Linear Distance Travelled (ft)
13mm shear non-leached	3.7	4582
13mm shear deep-leached	5.4	6765
Stinger non-leached	41.7	52189
Stinger deep-leached	45.8	57429

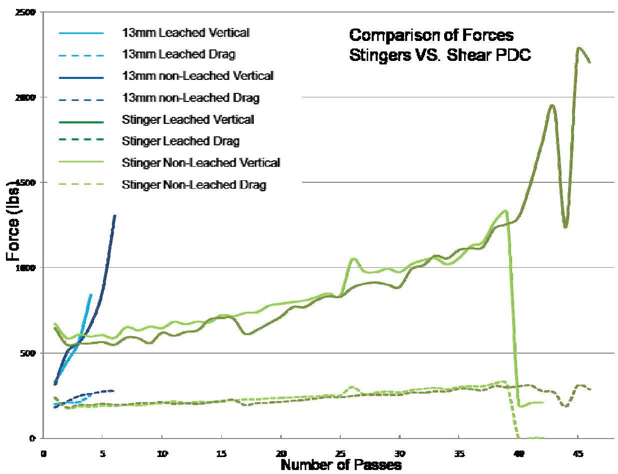

Figure 12: Plot of relative force vs. pass number for shear and Stinger PDC cutters.

The results of this testing show that the Stinger cutter has the ability to cut dry and to dramatically outperform shear cutters in hot testing. Deep leeching of the Stinger provides added thermal stability allowing it to survive 10% more passes across the granite.

Photos of the non-leached and leached shear cutters and non-leached Stinger following the test are presented in Figure 13. A photo of the Stinger cutter after 25 passes is shown in Figure 14. The Stinger PDC clearly demonstrates its ability to conduct heat away from the cutting surface and operate efficiently at extreme temperatures.

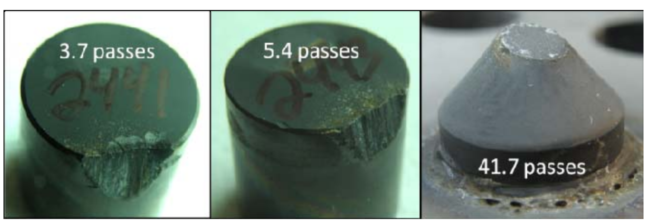

Figure 13: Non-leached, deep leached and stinger cutters after burn out during VTL testing.

Figure 14. Stinger cutter at 25 passes during VTL hot testing.

Bit Design and Testing

Laboratory test results as presented above indicated that the Stinger cutter should outperform standard non-leached and leached shear cutters in field applications. Experience in surface mining and road milling applications showed the Stinger to be superior to similar components manufactured from WC, however application of the Stinger to drill bit design was more challenging, because an entirely new mode of rock disintegration is at play Initial designs around conventional shear bit profiles presented many issues. The significant change in cutter design and orientation presented a number of engineering challenges that had to be overcome. The 17 degree forward rake angle required a completely different cutter pocket orientation compared to conventional PDC bit designs. The pocket depth led to interference at conventional cone angles. Cutter coverage over the gauge presented challenges in obtaining sufficient cutter volume and tip density to adequately cut a full-gauge hole without overloading the cutter. Most of these problems were solved by adopting a flat profile as shown on the first successful Stinger bit (Figure 15), designed with 5 blades, 5 nozzles and 14 Stingers. The gauge area was fitted with shear PDCs to maintain full gauge hole.

Figure 15. Stinger bit and blade detail after testing at Terra Tek geomechanics laboratory.

Testing of the Stinger bit was undertaken at Terra Tek Geomechanics Laboratory, where bit designs can be tested in an environment simulating downhole pressure conditions.

The target rock sample was placed into a pressure chamber with the bit and confining pressure of 5000 psi was applied. Borehole pressure was maintained at 4000 psi using water-based mud flowing at 350 GPM. Rock samples that were tested included Carthage Marble, Mancos Shale, Terra Tek sandstone (equivalent to Crab Orchard SS) and Sierra White Granite.

Initial test results were positive with the bit drilling in a stable manner (no whirl or vibrations) and showing a smooth bore wall and bottom hole pattern. Close inspection of the cutting structure showed no wear other than slight polishing of the PDCs. Drilling results are presented in Table 2. ROP values observed by the Stinger bit (albeit in a controlled environment) are an order of magnitude greater than those reported by Geodynamics Inc. during drilling of the Habanero and Jolokia wells in granite, where average ROPs of about 6 to 8 ft/hr were observed using TCI bits at similar WOB. While an order of magnitude ROP improvement would not be anticipated in field tests, these results show a considerable window for significant ROP and bit life gains.

Table 2. Results of Stinger bit testing in various rocks under confining pressure of 5000psi.

Rock Type	RPM	WOB (klbs)	MSE (kpsi)	ROP (ft/hr)
Mancos Shale	120	20	35-57	85
Carthage Marble	120	30	63-110	49
Terra Tek Sandstone	120	40	60-90	55
Sierra White Granite	120	40	52-82	47
Sierra White Granite	120	50	52-82	70

Cuttings produced during the testing were generally large (Figure 16) compared to cuttings produced by shear bits tested under analogous conditions. Shear bits typically produce finer cuttings, indicating that the cutting mechanism of the Stinger bits is significantly different. The remaining core of rock forming the bottom-hole pattern was sectioned through its axis following the test, revealing fine cracks radiating out from the cutter grooves.

Figure 16. Cuttings samples from confined pressure drilling with a Stinger bit in Sierra White Granite (left) and Terra Tek sandstone. Scale in Inches.

This seems to indicate that the cutter tip is wedging and ploughing the rock apart, causing some ‘spalling’ of the rock surface, leading to larger chips. It also suggests that the rock is compromised below the depth at which chips are being removed, allowing easier removal on the following pass of the cutter(s). Consequently, low mechanical specific energy values were recorded indicating that the rock material is being removed in an efficient manner.

Conclusions

Accelerated abrasion testing leads to the following conclusions:

The Stinger cutter exhibits reduced vertical and drag forces compared to conventional shear cutters when tested on the VTL.

The Stinger cutter has significantly improved abrasion resistance during extended wet testing on the VTL.

The Stinger cutter shows far higher linear footage before burn out in dry/hot testing compared to conventional PDC.

Laboratory testing at Terra Tek showed the Stinger bit to successfully cut hard abrasive rocks with no observable wear.

All this suggests that Stinger PDCs may represent a significant step toward the goal of long-life bits for hard formations in hot environments. Obviously additional test-driven, iterative improvements to Stinger bit design and understanding are needed to attain the longevity and footage demanded for geothermal applications.

Further Work

Material development and VTL testing will continue to further enhance the Stinger durability.

Additional tests are planned at Terra Tek to further develop bit designs and improve mechanical efficiency.

Field testing of Stinger bits is planned to start early 2010, with additional wells in harder, hotter locations including geothermal wells in Australia in mid-to-late 2010.

Investigate the feasibility of implementing Stinger PDCs in roller cone bits and hammer bits. Development of 'hybrid' bits; combining stinger and shear cutters in tandem to more efficiently compromise and remove rock materials.

Acknowledgments

The authors would like to thank the following for their help with this paper:

- Thomas Morris - VTL laboratory and testing.
- Francis Leany and Casey Webb - bit design and Terra Tek testing.
- Joe Fox – EGS Project Manager.
- Brett O'Leary - Geodynamics Drilling Engineer.

Partial funding for development and testing of the Stinger was supplied by a DOE grant for EGS development.

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