VERY LOW FRICTION SMALL RADIUS DOME CUTTERS FOR PERCUSSION BITS

PHASE II DEVELOPMENT EFFORTS

Prepared by David S. Pixton
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BACKGROUND

Basic Concept

When drilling with a percussion or roller-cone bit, penetration of the drill depends on its ability to crush and crack the rock formation being drilled. Initial penetration of the formation occurs primarily by crushing of the rock beneath the cutters of the bit. As penetration continues, the crushed zone increases in size and transmits force to the surrounding rock, causing cracks to form around the crushed zone.¹ The crushed and cracked zones grow as the cutter continues to penetrate, creating free particles. Depending on the loading geometry these particles may then be liberated from the cutting zone, or retained within it. If retained by frictional forces, they are further crushed under continued loading and transfer energy from the bit to the underlying rock. Because of their structure this crushed zone distributes that force as the tool continues to penetrate, and effectively become a blunt extension of the cutter.

Additional crushing of particles held under the bit by geometric and frictional constraints absorbs a significant portion of the energy required for penetration of the cutters. The movement of such particles from the cutting zone relieves confinement on the underlying rock (which may otherwise reach pressures of over 20,000 psi), lowering its resistance and concurrently lowering the forces required to achieve penetration. Two approaches that increase the mobility of the cuttings under the cutter are to decrease the wedge angle of the cutter (in effect making a sharper cutter) and decrease the coefficient of friction between the cutter and the rock formation. Both of these factors will lower cutting forces and increase rate of penetration (ROP) regardless of other rock characteristics.

Figure 1 depicts the benefits of using a low friction cutter as opposed to a higher friction cutter. As shown, the low coefficient of friction offered by a polished cutter allows rock cuttings to be removed more quickly than is possible with current higher friction tools. An example of current technology that corroborates this concept at least in part is a polished flat drag bit cutter patented by Baker Hughes in 1995². This relatively new development claims increased cutting efficiency and improved chip formation. Improved chip regularity indicates a lower specific energy of formation than is possible with prior art drag bit cutters. The profile of the rock surface left behind the cutter exhibits less relief than the profiles of prior art cutters. The surfaces of the Baker Hughes cutting elements were polished to a mirror finish, which greatly reduces the adhesion of the chips as they form. This approach claims to yield a higher ROP, because the cuttings move quickly away from the point where they are formed. Drag bit technology, while fundamentally different from percussion drilling, still requires high strength, high abrasion-resistant inserts for economical drilling. The super hard cutting surface was polished to at least a 10 μ inch surface variation with 0.5 μ inch preferred.

As a second benefit of reduced friction cutters, decreased friction should decrease the thermal and mechanical loading on the cutting inserts in hard rock. Frictional heating of polycrystalline diamond inserts is destructive to the diamond coating. With decreased friction between the insert and the rock, frictional heating will decrease. Moreover, improved penetration in harder formations due to lower friction may allow use of lower weight on bit, which will decrease cutter loading. Thirdly, the mechanical robustness of the cutter is expected to improve as the cutter is polished. Polishing will diminish surface imperfections that act as stress risers and crack initiation sites. Hence, the fatigue strength of the cutters is expected to increase, resulting in a longer useful life, and less down-time due to bit failure.

It should be noted that these approaches to increasing ROP are only useful if the surface finish and sharpness are maintained over a significant portion of the life of the cutter. The only material that is hard enough to maintain its shape and surface finish while drilling in hard, abrasive formations is diamond. Even tungsten carbide, which is widely used in drilling, wears rapidly, causing dulling of the cutter and loss of initial surface finish.

Polycrystalline diamond (PCD) coatings have been developed to improve the wear resistance of drill cutters.^{iii, iv} Such coatings have been used to great advantage in certain rotary and percussion drilling applications. However, in hard, abrasive formations, this type of cutter still exhibits wear. High stresses placed on diamond-to-diamond bonds (which bond diamond crystals together) cause eventual failure of these bonds. Microcracks occur within the coating, followed by progressive loss of the coating in chipped regions. Moreover, industry experience has shown that the sharper the cutter, the lower the service life of the PCD coating. This is due, at least in large part, to residual stresses formed within the cutter during the coating process. Once the coating is lost, the underlying tungsten carbide cutter is exposed and wear proceeds more rapidly. These factors have seriously limited the application of such coatings in hard rock regions, and have largely deprived such regions of the improved wear resistance and increased rate of penetration offered by PCD inserts.

Project Background

For several years, Novatek has been actively pursuing development of new diamond materials^v that will extend both the life and application of diamond enhanced cutters, by allowing higher applied stress and sharper cutting element design. To better address the problems outlined above which limit hard rock application of diamond, Novatek has focused on the development of a suite of small tip-radius (sharp), polished PCD inserts for use as percussion and roller cone cutters. This development effort has required fundamental and applied research to determine the extent of benefit deriving from reduced friction of the cutters. It has also required materials research and development to accomplish heretofore prohibitive levels of PCD cutter sharpness.

Initial fundamental studies begun in the fall of 1996, and completed at the University of Missouri Rolla's Rock Mechanics and Explosives Research Center (UMR-RMERC), have shown that indeed, there is a correlation between the surface roughness of the cutter and the force required to penetrate at least some rock types. Figure 2 shows these initial results for specimens of Holston Limestone. These results suggest that for this formation, polished cutters can allow use of lower weight on bit to drill without penalizing penetration rate; conversely, at typical weight on bit levels, penetration should increase. Similar trends were obtained for other rock samples, including Roubidoux Sandstone, Salem Limestone, Sioux Quartzite, and Dresser Basalt, although some of the data showed inconclusive or even slightly negative relationships.

Initial studies have also shown that shaped (non-planar) polycrystalline diamond inserts can be polished to a very good surface finish, although initial polishing attempts were quite labor-intensive, due to the hardness of the diamond coating and the shape of the polished surface. As for the ability of the PCD coating to maintain a polish during the drilling process, repeated observation of percussion bits populated with polycrystalline diamond coated cutters have shown that the diamond coating does not degrade in surface finish over the period of usage. Rather, it polishes to a certain extent in the areas of highest contact between the cutter and the rock.

Phase II Objectives

The overall goal of this program is to provide industry with a new generation of diamond enhanced drill inserts which increase rate of penetration (ROP) and bit life, and which allow use of PCD in harder rock types. A means of economically polishing shaped PCD inserts, coupled with materials improvements, are the specific mechanisms for accomplishing this overall objective.

Based on the above discussion, the primary objectives of the current research are:

- **to determine the diamond coating design and polishing means which will result in the most favorable improvements in drilling rate with respect to cost.**
- **to catalog the effectiveness of polished inserts in a variety of rock types.**

The results obtained in the pursuit of these objectives may have further implications with respect to the design of bits for maximum penetration rate. However, at this point, no dramatic changes in bit design are anticipated as being needed to fully benefit from the improved cutter technology.

Approach

The overall approach of this research has been to seek and apply understanding of the physical properties and chemistry of PCD coated cutters that will lead to improvements in overall drilling efficiency. Particular attention is given to the condition of the cutter's surface.

The surface roughness of a PCD coating is controlled both by the selection of PCD processing parameters and by post-processing techniques such as polishing the surface after the coating has been applied. The nature of the coating, whether single or multiple layered, with or without interlayers, or with coarse or fine grain size, will affect the coating's ability to take a polish. Furthermore, the formulation of the coating has been found to have a great influence on the overall robustness of the cutter. Hence, it is necessary to consider each of the above interrelated factors when moving toward the desired end result.

For this reason, the basic approach of the present research has been to seek concurrent improvements in coating formulation, geometry, and surface finish. Fundamental research using rock penetration tests and basic single cutter evaluations were used to guide initial decisions. UMR-RMERC has played an instrumental role in this fundamental work, and in providing expertise in rock failure analysis. Initial tests are followed by validation under the more complex conditions found in actual drilling applications. Both percussion and rotary (roller-cone) drilling have been chosen as suitable beds for testing and introducing improved cutters. Industry interest in improvements to PCD cutters is sufficient to provide for test sites as "in-kind" contributions to the research.

Final validation of the new technologies, however beneficial, must include a comparison of costs of additional processes to the gains achieved. Therefore, development of polishing methods that are economically favorable has been of prime importance.

RESEARCH RESULTS

Polishing Developments

Previous efforts to polish shaped PCD inserts yielded a high polish at a high cost. Under the current research program, several additional methods of polishing have been investigated, including traditional finishing processes such as tumbling, lapping, and grinding, as well as other more proprietary processes. The best of these processes have duplicated the highest degree of polish accomplished earlier (see Figure 2), but at much lower cost, and higher repeatability. A key to improving cost and repeatability has been the automation of the polishing process. Figure 3 shows a prototype machine that has been built to polish PCD cutters, which utilizes the polishing technique just mentioned. As shown, this machine offers several independent degrees of freedom for polishing convex or concave axisymmetric cutter shapes.¹ It is capable of generating very high relative speed between PCD cutter and the polishing wheel, which is necessary for obtaining a high polish.

Using this polishing technology, a surface finish of 0.23-0.27 micrometers (Ra) is currently achievable in less than ten minutes of polishing. This suggests that the benefits of polishing may be obtained rather inexpensively, as the process is scaled up to higher quantities. Figure 4 illustrates the mirror-like finish available by this process. This finish is similar to the level of polish offered by a commercially available polisher for flat diamond parts. Referring again to Figure 2, such a polish could increase the rate of penetration of the cutter by as much as a factor of two or three in medium to hard rocks.

To quantify the actual effect of the polished cutter in a full-scale field test, two 6-1/2 inch percussion bits were prepared and fully populated with polished cutters. One of these bits is shown in Figure 5. The two bits were identical in geometry and polish (cutters were full rounds 3/4" in diameter); however, the two varied in the diamond mix used to coat the cutters. The first bit was populated with cutters from the "A" material described below; the second was populated with "C" formulation cutters. These two bits were run in well-bedded graphite and shale formations, with occasional stringers of quartz. Table 1 shows the results of the bit runs of these two bits, along with the average of five bit runs with standard PCD cutters. As shown, the two polished cutter bits did not conclusively exhibit longer life than the standard PCD cutters. ROP data is not yet available on these wells.

PCD Cutter Type	Footage, ft.
Polished "A" mix	1920
Polished "C" mix	2290
Unpolished "A" mix (average, std. Deviation)	2390, 1376

Table 1. Performance of Polished Cutter Percussion Bits vs. Standard Cutter Bits

¹ It is anticipated that anaxisymmetric shapes may also be polished on this machine with modifications to the control of the primary spindle.

A third bit has also been built, this time a tri-cone rock bit for oil and gas drilling. Because of the difficulty of obtaining test sites for new products in today's market, the bit manufacturer chose the conservative approach of testing three different iterations of cutters in the same bit. Of these three iterations, only one was polished. Hence the information to be gathered in this test will be related to life and survivability of the polished cutters versus the other iterations (no meaningful ROP data is expected). The geometry of the cutters in this bit was also conservatively specified to be full radius rounds, rather than the more aggressive shapes developed. This bit has now been out in the field for a few months, but has yet to be run due to adverse economic drivers. Once this bit is successfully run, and confidence is gained in the new cutters, it is Novatek's intention to build a bit fully populated with polished cutters, which will be able to yield data regarding ROP improvement.

Materials Developments

Polycrystalline diamond coatings may be engineered to give specific qualities, including polishability, polish retention, and mechanical robustness. All three of these qualities have been shown to improve with a recently developed coating formulation. Figure 6 shows the results of a full-scale bit test, wherein three different types of cutters are placed in the same bit and tested in the laboratory for survivability under extreme loads. As shown, cutters employing coating "C", the new mix formulated specifically for higher abrasion resistance, survived measurably better than those coated with Novatek's standard material "A" and another test material "B". This test suggests that, particularly in hard rock, formulation "C" provides for a more robust cutter. Figure 7 shows this same material, compared to material "A" in a severe abrasion test. In this test, cutters coated with each material were polished to a fine polish, then blasted aggressively for a given amount of time using aluminum oxide blast media. An unpolished cutter coated with standard material "A" was also blasted as a control. As is shown, the surface roughness of the cutters does degrade in this test; however formulation "C" degrades much more slowly than does "A" and maintains a level of polish over the course of the test that is finer than the as-coated insert. It is unknown how well this particular test imitates conditions down-hole during actual drilling; however this test does verify the superiority of the "C" formulation under abrasive rock conditions.

Other significant materials improvements have been made to allow the successful use of more aggressive PCD coated cutter shapes in field applications. As mentioned earlier, PCD coatings have been heretofore limited to relatively large radius cutters, due to inherent materials mismatch and processing difficulties. However, improved coatings and manufacturing processes have been developed which allow the use of sharper profiles for the coated substrate. Figure 8 shows some of the cutters that Novatek has produced for use in rock cutting structures. Each pair of cutters shown in the figure includes a hemispherical topped cutter, which in most cases represents the current art in PCD inserts, and a more aggressive (sharper) version of that size of cutter. Though these sharper cutters have only recently been introduced into field bits, and have little field data compiled, initial customer feedback has been very positive. These sharper cutters have become a part of Novatek's standard product line and are receiving steadily increasing acceptance into tricone bits.

CONCLUSIONS

From the above discussion, it may be concluded that:

1. Materials and processing improvements attained during the course of this project have resulted in greater robustness of the PCD coating. This greater robustness has allowed application of the highly wear resistant PCD coating to more aggressively shaped cutter structures.
2. Materials improvements can be made to improve the ability of the PCD cutter to retain a high degree of polish, and at the same time improve the overall robustness of the cutter.
3. Non-planar PCD coated cutters may be polished at reasonably low cost.
4. Polishing domed percussion cutters brings no apparent benefit to the life of a percussion bit in at least some formations.
5. More field experience is needed to determine the effect of polishing PCD cutters on rate of penetration of full-scale bits in real world drilling applications.

FUTURE PLANS

Future commercialization efforts will be focused in three areas. The first area of focus will be the expansion of the current product line of aggressive cutters. This effort has already commenced and will be responsive to increasing customer need and customer requests for different shapes. The second area of focus will be the continued evaluation of polished cutters in field tests. Since the tests to date are either still pending or are inconclusive regarding ROP benefits, more field experience is necessary to determine the usefulness of polished cutters in real life conditions. Should this further experience yield economically positive results, more work will then be expended on introducing polished cutters into the marketplace. This third area of focus will include fine-tuning of current polishing technology and further cost reduction. Improvements to be made in this area include the following:

- Improving operation of the polishing machine to be completely "hands off"
- Replicating the polishing station to better utilize the polishing machine's capacity
- Fine-tuning polishing wheels and procedure for production lots
- Extending polishing techniques from domed parts to more aggressive parts (and possibly anaxisymmetric geometries)

Introduction of the aggressive cutters produced in this study into production bits has proven to be nearly transparent, since the cutters are a direct replacement for the cutting elements on existing bits. They do not require the significant investment in support equipment that often accompanies a major change in drilling efficiency. Once proven, the polished diamond cutters are expected to enjoy similar ease of introduction.

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ILLUSTRATIONS

Figure 1. High Rock Cutter Friction Impedes the Removal of Drill Cuttings. Each failure event (e.g. chips) tends to be held in place by rock-cutter friction, impeding the formation and removal of the next chip. The crushed zone is held in place by the rock-cutter friction.

Figure 2. Energy Required to Drive a 0.75 inch Domed Cutter into Holston Limestone a Distance of 0.25 inches, as a Function of Surface Finish of the Cutter.

Figure 3. Prototype Polishing Machine for Shaped PCD Cutters.

Figure 4. 0.75 inch Domed Percussion Cutters Polished to 0.25 μm Ra

Figure 5. Test Bit for Polished Percussion Cutters

Figure 6. Overload Durability Test for New Formulation PCD Coating ("C" Formulation). Drilling was done with a roller cone bit in quartzite at 100 rpm.

Figure 7. Polish Durability Test for New Formulation PCD Coating ("C" Formulation).

Figure 8. Aggressive and Current-Art Cutters in Field Applications.