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DEVELOPMENT OF ADVANCED SYNTHETIC-DIAMOND DRILL BITS FOR HARD-ROCK DRILLING

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ABSTRACT

Cooperative research is currently underway among five drill bit companies and Sandia National Laboratories to improve synthetic-diamond drill bits for hard-rock applications. This work, sponsored by the U.S. Department of Energy and the individual bit companies, is aimed at improving performance and bit life in harder rock than has previously been possible to drill effectively with synthetic-diamond drill bits. The goal is to extend to harder rocks the economic advantages seen in using synthetic-diamond drill bits in soft and medium rock formations. Four projects are being conducted under this research program. Each project is investigating a different area of synthetic-diamond bit technology that builds on the current technology base and market interests of the individual companies involved.

INTRODUCTION

If the survivability of PDC and other synthetic-diamond drill bits could be improved for hard-rock conditions, the more efficient cutting mechanisms inherent to such bits could be used to advantage in reducing drilling costs. Because drilling costs, in general, are very high in hard rocks, the incentive to improve the technology is great. Reduced hard-rock drilling costs would increase the United States' energy supply by making both geothermal resources and deep oil and gas more economical to access.

DESCRIPTION OF THE PROGRAM

The Advanced Synthetic-Diamond Drill Bit Program currently consists of the following projects. These projects have been described in detail in Glowka and Schafer (1993) and Schafer and Glowka (1994).

- *Optimization of PDC Claw Cutters with Dennis Tool Company*

The objective of this cooperative project is to maximize the benefit of the claws and minimize overall and localized cutter stresses in PDC claw cutters (see Delwiche et al. (1992) for a description of claw cutters). Numerical modeling of various claw geometries is being conducted to calculate thermal and mechanical stresses under typical operating conditions. Single-cutter wear tests are also being conducted with various claw geometries in order to rank the wear resistance of the geometries and verify the numerical results. Dennis Tool Company is designing and manufacturing the cutters for this project. Sandia is performing the numerical analysis and single-cutter testing. Sandia is also providing DOE funding to Dennis Tool Company on a cost-shared basis.

- *Optimization of Track-Set Bits with Security DBS*

The objective of this cooperative project is to maximize the cutter tracking effect, minimize bit vibration and wobble, and maintain rapid rock penetration with Track-Set bits (see Weaver (1993) for a description of Track-Set bits). Single-cutter testing is being conducted by Sandia to provide quantitative cutter performance characteristics to guide bit design. Security DBS is incorporating these cutting parameters into computer software that will be used to design Track-Set bits. Sandia is also providing DOE funding to Security DBS on a cost-shared basis.

- *Advanced TSP Drill Bit Development with Maurer Engineering and Slimdril International*

The objective of this cooperative project is to maximize thermally stable polycrystalline (TSP) diamond bit performance and identify optimal cutter configurations and bit design guidelines for hard-rock applications (see Cohen et al. (1993) for a description of Maurer's past work on TSP bits). Sandia is wear-testing single TSP cutters of various shapes and sizes to provide ranking with respect to wear and impact-damage resistance. Sandia is also providing DOE funding to Maurer Engineering/Slimhole International on a cost-shared basis. Maurer Engineering and Slimhole International are manufacturing and testing TSP bits with various cutter configurations to identify optimal cutter placement guidelines and to confirm the single-cutter wear test results. DeBeers and General Electric are providing TSP test cutters at no cost.

- *Optimization of Impregnated-Diamond Drill Bits with Hughes Christensen Company*

The objective of this cooperative project is to increase penetration rates with impregnated-diamond bits while maintaining impact and wear resistance in hard-rock applications. Hughes Christensen is conducting drilling tests with various diamond and matrix designs, evaluating a proprietary diamond coating technology that aids diamond retention in the matrix, and developing mechanistic models of the impregnated-diamond rock-cutting process. Hughes Christensen is contracting with Dr. Fred Appl to perform the model development. Sandia is providing DOE funding to Hughes Christensen on a cost-shared basis.

• *Other Participants*

Amoco Production Research is under contract with Sandia to provide drilling time at their Catoosa Test Facility in order to field test bits developed under this program. The facility contains access to over 2,000 feet of well-documented lithologies that contain hard rock intervals and transition zones from soft to hard rock.

There were initially eight participating bit companies in this program. Due to corporate restructuring and consolidation, the number of participating companies is now five, as outlined above. In addition, two original participants in the program, Smith International and Magadiamond, have undergone corporate restructuring that did not leave them with adequate resources to continue participation in the program. Consequently, their cooperative project on fundamental bit failure and rock cutting mechanisms in hard rock has been eliminated from the program.

PROJECT RESULTS TO DATE

The program outlined above has been underway for two years. This section presents the progress made in the various projects thus far.

Optimization of PDC Claw Cutters

Numerical Stress Modeling

Thermal and mechanical stress modeling has been conducted for nine claw cutter configurations. A typical configuration is shown in Figure 1. An advanced automated mesh generation capability developed at Sandia was used to construct the numerical models. Each finite-element model consists of over 16,000 elements. Seen in this figure are the claw-cutter design parameters that were changed for the various configurations: diamond layer thickness; tungsten carbide groove depth; groove width; distance between grooves; and number of grooves. By calculating stresses for various combinations of these parameters, equations can be derived that allow interpolation of stresses for parameter values that lie within the bounds of those used in the numerical calculations. The thermal and mechanical conditions for which the calculations were made were chosen as typical of challenging,

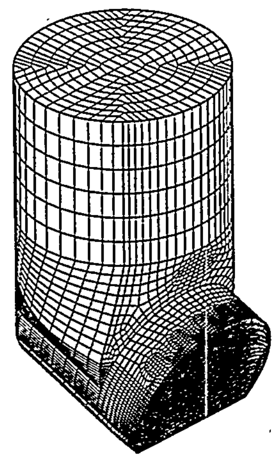

Figure 1 - Typical claw-cutter finite-element mesh.

hard-rock drilling. They are based on previous Sandia work by Glowka and Stone (1985, 1986) and recent experience with single-cutter testing.

The thermal stress analysis has been completed. Although the results are complex and difficult to convey in a summary article such as this, it is possible to present some general conclusions. Table I shows the maximum computed Von Mises stress for each of the selected claw cutter configurations. Note that the configurations with the thinnest diamond layers have the highest calculated thermal stress. This is a reasonable conclusion based on the fact that the thermal stresses are primarily a product of the thermal gradients in the cutter and the differential thermal expansion between the tungsten carbide and the diamond structure. The effects of the other design parameters are more complex and will require further study to fully explain.

TABLE I
COMPUTED MAXIMUM CLAW CUTTER THERMAL STRESSES

Configuration	Diamond Thickness, in	Groove Depth, in	Groove Width, in	Dist. Between Grooves, in	No. of Grooves	Maximum Stress, ksi
1	0.020	0.060	0.039	0.039	6	21.6
2	0.005	0.020	0.039	0.020	8	37.4
3	0.040	0.100	0.039	0.071	4	24.8
4	0.005	0.100	0.020	0.040	8	31.1
5	0.060	0.060	0.020	0.020	12	17.7
6	0.020	0.020	0.020	0.087	4	22.7
7	0.040	0.020	0.078	0.039	4	19.2
8	0.020	0.100	0.102	0.020	4	19.1
9	0.005	0.060	0.102	0.102	2	38.5

Before a claw cutter configuration can be selected based on stress, it will be necessary to complete the mechanical stress analysis. The principle of superposition can then be used to combine the thermal and mechanical stress results to determine the total stress field for each cutter configuration. Equations can then be developed that describe the effects of the various design parameters on cutter stresses.

Single-Cutter Wear Testing

In order to perform wear-testing of PDC claw cutters, a test procedure was developed using the vertical lathe shown in Figure 2. A large 3 ft X 3 ft X 3 ft block of Sierra White Granite was mounted on the rotary table. A triaxial dynamometer mounted on the traveling head was fitted with the test cutter. The traveling head moved at a fixed radial speed across the top surface of the rock as the rock was rotated. The cutter therefore made tightly wound spiral cuts across the top surface of the rock while triaxial cutter forces were measured. A vertical, 2.5-inch diameter hole was drilled in the center of the rock prior to the tests in order to remove that portion of the rock that would have required operating the cutter in a very tight radius. Also, the outside corners of the rock were removed prior to each pass with a different cutter in order to prevent the test cutter from having to perform interrupted cuts. Water was directed through a 0.25-inch nozzle at the cutter/rock interface at a rate of 0.08 gpm in order to wet the rock surface and control dust.

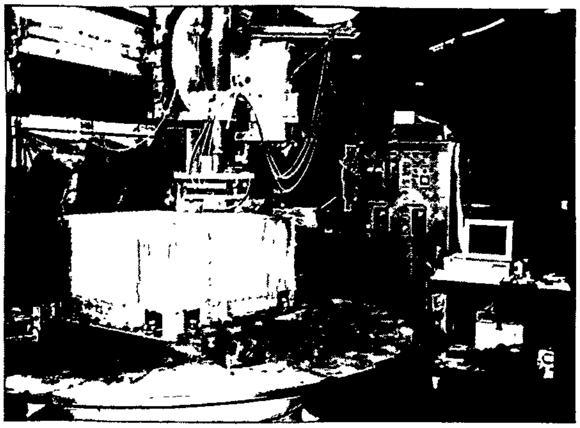

Figure 2 - Vertical lathe set-up used to wear-test single PDC and TSP cutters.

A nominal vertical depth of cut of 0.060 inches and a radial feed of 0.080 inches/revolution were adopted as standard cutting conditions. These conditions resulted in rock removal rates typical of those for a PDC cutter on a bit drilling at 30 ft/hr. Each pass of the cutter over the rock surface represented about 1000 ft of linear cutting, sufficient to cause a measurable amount of cutter wear with each pass. The cutter wearflat dimensions (length, width, and area) were measured after each pass using a video-microscope measurement system.

Baseline cutter wear rates were established with conventional, 1/2-inch, chamfered PDC cutter compacts (GE model 2741). Data were obtained at two different rotary table speeds, 10 and 20 RPM. Because the rotary speed was held constant for a given test, the linear speed of the cutter varied from a maximum along the outer radius of the rock to a minimum near the center of the rock. The linear speed of the cutter thus varied from 1.3 to 18.8 ft/sec at 10 RPM and 2.6 to 37.7 ft/sec at 20 RPM. In order to ensure that the cutter wear results were not cutter-dependent, each of the two cutter compacts were tested both at the lower and higher rotary speeds, with the compact being rotated 180° in the cutter holder between tests. Miniature (0.010-inch diameter) thermocouples were mounted in the compacts through an electro-discharge-machined (EDM) hole drilled through the back of the compact up to, but not through, the diamond layer. The EDM hole was oriented such that the wearflat would actually wear into the thermocouple at some point during the wear process.

Results of these baseline tests with the conventional PDC compacts are shown in Figures 3 and 4. Figure 3 shows the cutter wear volume as a function of cutting distance, with the total cutting distance representing 10-15 passes of the cutter over the rock surface. Testing for each cutter was terminated when the wearflat reached the point that the cutter penetrating (vertical) force exceeded 1000 lb, the

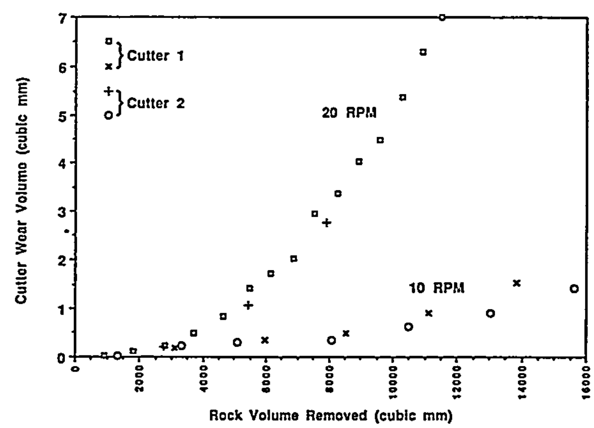

Figure 3 - Conventional PDC cutter wear rates measured on the vertical lathe in Sierra White Granite at two rotary speeds.

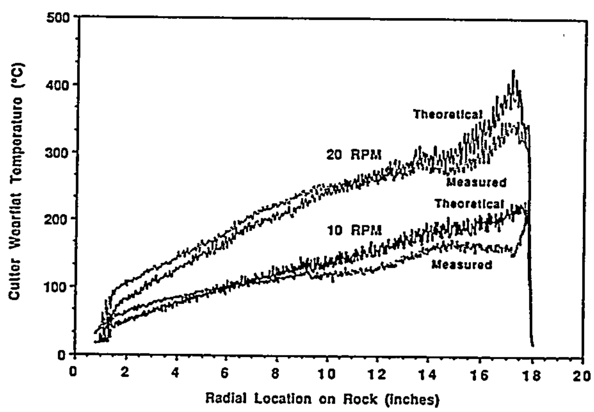

Figure 4 - Theoretical and measured cutter wearflat temperatures for conventional PDC cutters in Sierra White Granite.

maximum safe force for the vertical lathe. It is seen for a given rotary table speed that the results are highly repeatable and that the effect of rotary speed is profound. Wear rates at the higher rotary speed are about 10 times higher than wear rates at the lower rotary speed. Figure 4 suggests the probable cause for this phenomenon.

In Figure 4, the cutter wearflat temperatures are plotted for the pass just before the wearflat reached the thermocouple and destroyed it. In addition to the experimental data, the theoretical wearflat temperatures are plotted based on the measured cutter forces and speeds and a temperature model previously developed by Glowka and Stone (1985). Several points can be made from these results. First, there is excellent agreement between the measured and calculated wearflat temperatures. Second, the cutter temperatures depend on the cutter's radial position on the rock and thus its linear speed. Third, the cutter temperatures are significantly higher at 20 RPM than at 10 RPM. This is the probable cause for the accelerated wear rates experienced at the higher rotary speed. This conclusion agrees with the theory proposed by Glowka and Stone (1986) that thermally accelerated cutter wear occurs when wearflat temperatures exceed 350°C.

Cutter Wear Facility Development

Considerable time was spent in developing the wear test procedures described above with the vertical lathe. Although the procedures were found capable of developing significant, repeatable wearflats, several deficiencies in the method were identified that caused us to question the technique. These include the following:

1) The linear speed effect described above and the inability to maintain a constant linear speed added a degree of uncertainty to the results because it is possible that various cutter configurations would exhibit different critical temperatures above which thermally accelerated wear occurs. This would have made it difficult to ensure that experimental cutters were being operated below their critical temperatures without performing tests at multiple rotary table speeds with each cutter configuration.

2) Although quite stiff, the vertical lathe did exhibit enough flexibility at high penetrating forces to make it difficult to maintain a constant depth of cut between one pass and the next pass as the cutter wore. Depths of cut typically varied by 10-30%, which was deemed unacceptable for comparative wear testing.

3) It was not possible in these tests to hydraulically cool the cutter to the same degree as on a bit drilling with drilling mud. Although a low-pressure water jet was directed at the cutter, the jet neither enveloped the cutter not impacted it with velocities typical of those encountered downhole in actual drilling.

4) The character of the cutter interaction simulated in these tests was not similar enough to that experienced on a real bit to convince us that the measured wear rates could be used to quantitatively predict wear downhole on a real bit.

Because of these deficiencies, we embarked on the development of the Cutter Wear Test Facility (CWTF) shown schematically in Figure 5. This facility is basically a small rotary drilling machine that can be used to efficiently drill approximately one hundred 3-inch diameter holes in a single 3 ft X 3 ft X 3 ft block of rock. The rock block is mounted on an air caster to enable it to be easily moved laterally between holes.

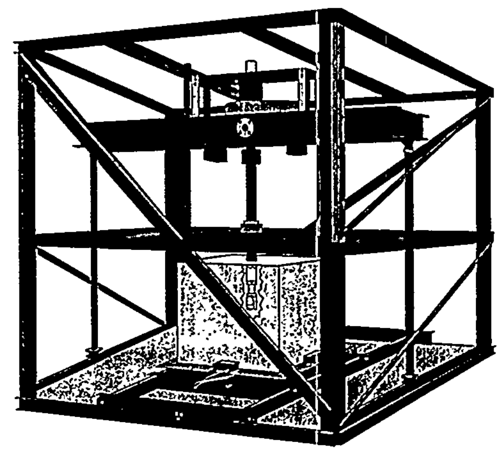

Figure 5 - Cutter Wear Test Facility under development.

The drill bit consists of three cutters and is similar to a core bit, with the test cutter situated radially between the inner and outer trim cutters at a radius of 1 inch. The test cutter thereby experiences cutter interaction similar to that on a full-face bit. The bit was designed and laterally balanced using Sandia's PDCWEAR code; see Glowka (1987, 1989a, 1989b).

The test cutter is mounted on a block instrumented with strain gages to allow triaxial cutter forces to be measured. All three cutters on the bit can also be fitted with one or more thermocouples to measure cutter temperatures. Slip rings are used to bring the strain gage signals and thermocouple signals off the rotary drill stem. Water or other liquids are used to cool the cutters and remove rock cuttings from the hole.

The machine is operable to 500 RPM to permit duplication of linear speeds typical of those seen near the gage of an 8-3/4 inch bit at 60 RPM. A weight-on-bit capability of 6,000 lb allows up to 2000 lb of penetrating force to be imposed on the test cutter. The maximum penetration rate is 160 ft/hr. The machine can be operated in two modes, constant penetration rate or constant weight-on-bit.

Construction of the machine is complete, and testing of standard PDC and claw cutters has begun.

Optimization of Track-Set PDC Bits

Linear single-cutter tests are underway using the horizontal milling machine shown in Figure 6. In these tests, a rock sample (typically 22 inches long X 10 inches wide X 4 inches tall) is placed on the translating table. A triaxial dynamometer is mounted to the fixed head and fitted with the test cutter. Linear cuts are performed at a fixed cutting speed of 2.4 inches/second, the table's maximum speed. This arrangement is the same as that used to study cutter interaction for conventional PDC bits by Glowka (1987, 1989a, 1989b). With these tests, the linear cuts are not long enough to cause measurable cutter wear over any given pass, even in hard, abrasive rock.

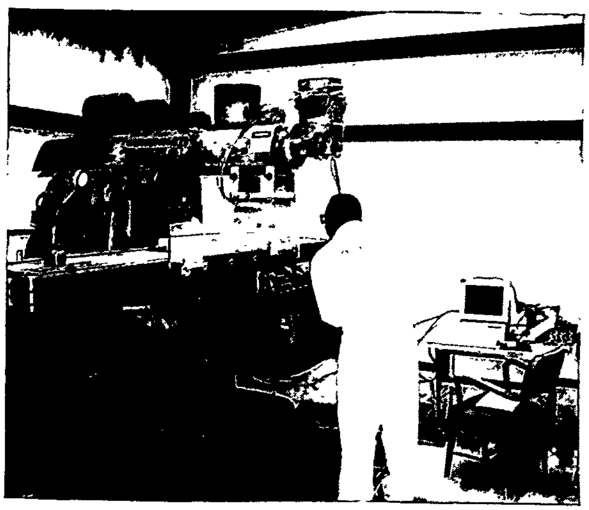

Figure 6 - Horizontal milling machine used to perform instrumented, linear, single-cutter tests for Track-Set bit design.

In this study, cutter interaction patterns typical of those that occur with Track-Set bits are being evaluated. Two such patterns for which data have been obtained are shown in Figure 7. In the engagement-angle tests, successive cuts are made at a constant depth of cut in the same track (or groove), thereby increasing the total groove depth (and thus engagement angle) with each pass. These tests are important in determining the effect of the groove depth on cutter forces as a function of the depth of cut (i.e., penetration per revolution). In the restoration-force tests, a cutter is displaced laterally with respect to an existing groove. This provides data on the lateral restoration force available to return a cutter to its running track when lateral bit vibration or wobble occurs. Data for both of these cutter interaction patterns were obtained with a sharp, 1/2-inch, chamfered PDC cutter at a 20° backrake for three rock types: Sierra White Granite, Tennessee Marble, and Berea Sandstone.

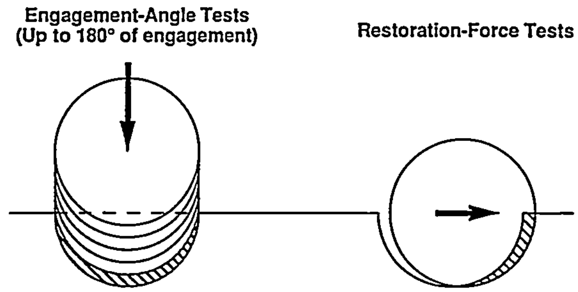

Figure 7 - Cutter-interaction patterns being evaluated in single-cutter tests for Track-Set bits.

Engagement-angle data are shown in Figures 8 and 9 for Sierra White Granite. Plotted here are penetrating (vertical) and drag (horizontal) forces as functions of the total groove depth and incremental depth of cut. Note that the forces seem to approach an asymptote as total groove depth increases. This is reasonable because of the shape of a round cutter. As the groove depth approaches a value equal to the compact radius times the cosine of the backrake angle (i.e., 0.24 inches), the engagement angle between the cutter and the rock approaches 180° and the circumferential contact length between the cutter and the rock approaches its maximum (one-half the circumference of the round compact).

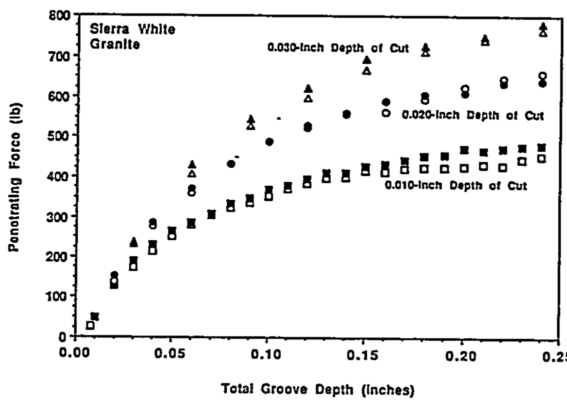

Figure 8 - Measured penetrating forces in single-cutter, engagement-angle tests in Sierra White Granite.

Typical restoration-force data are shown in Figure 10. Seen here are the lateral cutter forces measured as a function of the total groove depth and the lateral

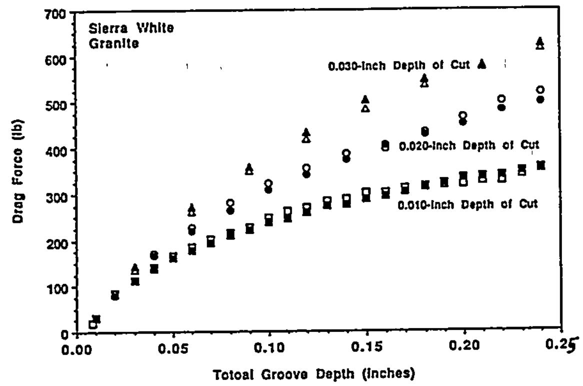

Figure 9 - Measured drag forces in single-cutter, engagement-angle tests in Sierra White Granite.

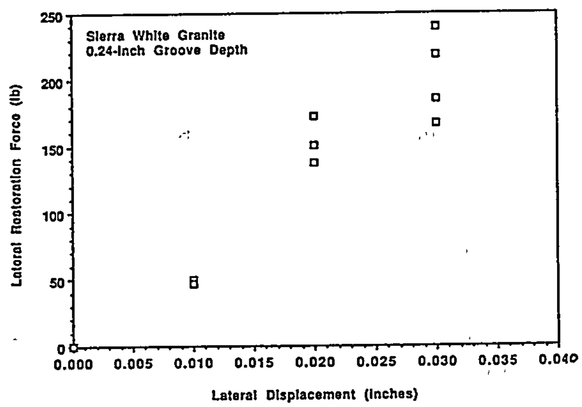

Figure 10 - Measured lateral restoration forces in single-cutter tests in Sierra White Granite.

displacement imposed on the cutter with respect to the groove centerline. Note that very small lateral displacements result in relatively high lateral forces. This confirms that with hard rock, significant restoration forces are available to push the cutters back into their tracks if bit vibration or wobble occurs.

Similar results to those described above were obtained with Tennessee Marble and Berea Sandstone. The force levels were, of course, found to be lower with these rock types, consistent with their lower compressive strengths. Measured compressive strengths for the three rock types were reported by Glowka (1987, 1989a) to be: 7,100 psi for Berea Sandstone; 17,800 psi for Tennessee Marble; and 21,500 psi for Sierra White Granite.

Security DBS is currently analyzing the single-cutter data so that it can be used to improve the force-balancing software they use to design PDC bits. This will make the software more directly applicable to the design of Track-Set bits.

Optimization of TSP Bits

The vertical-lathe cutter wear test procedure described previously was used to measure wear rates for several different TSP cutter configurations. The profiles of these configurations are shown in Figure 11. With the exception of the TSP disk configuration (not shown), these cutters were significantly smaller than typical PDC cutters, only 5-7 mm across. Consequently, the nominal depth of cut was reduced to 0.015 inches and the radial feed rate was reduced to 0.023 inches/revolution for tests with these configurations.

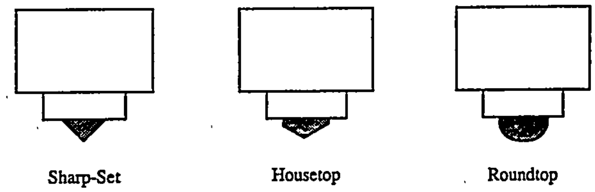

Figure 11 - Profiles of TSP cutters used in single-cutter wear tests. (TSP disk cutter not shown.)

The TSP disk cutter, on the other hand, was the same shape (round profile) and size (1/2-inch diameter) as a conventional PDC cutter. Also with this configuration, the TSP diamond was bonded to a thin (0.030 inch thick) wafer of tungsten carbide for support. In this case, the same nominal 0.060-inch depth of cut and 0.080-inch/rev feed rate were used as for the standard PDC cutters, allowing a direct comparison of wear rates to be made. All tests were performed in Sierra White Granite with a rotary table speed of 20 RPM.

Results for the small TSP cutter configurations are shown in Figure 12. Note that the housetop configuration experienced the lowest wear rates, followed by the 7-mm sharp-set, the GE silver top, and the roundtop configurations. These results cannot be compared with those of the conventional PDC cutters because of the significant size

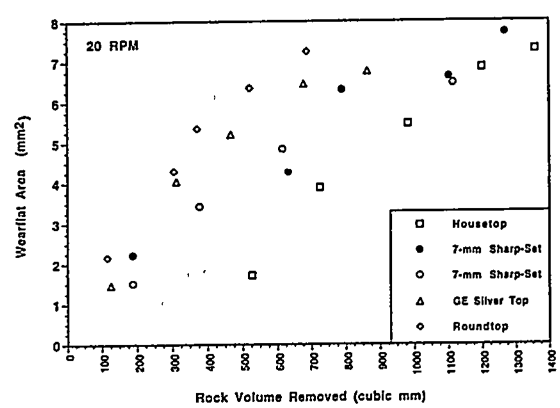

Figure 12 - Measured cutter wearflat areas for various small (5-7 mm) TSP cutters in Sierra White Granite.

differences and the different depths of cut and radial feed rates used.

Results for the TSP disk cutters are shown in Figure 13, where the wear rates are compared with those of the conventional PDC cutters. Note that the results were repeatable and that the TSP disk cutters wore at only about 15-20% of the wear rate of the PDC cutters. In fact, the TSP disk cutters at 20 RPM wore at almost the same low rate as the PDC cutters at 10 RPM (see Figure 3), indicating that the TSP disk cutters were not subject to the same thermal-wear threshold that the PDC cutters demonstrate.

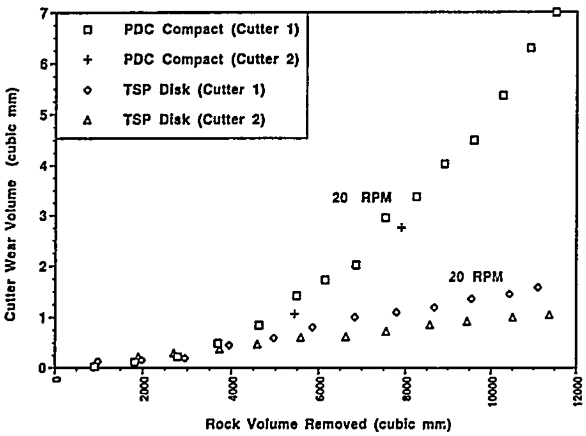

Figure 13 - Measured cutter wear rates of conventional PDC and TSP disk cutters in Sierra White Granite.

The TSP disk cutter tests were terminated when the wearflats reached the point that cutter forces were high enough to fracture the cutters, including the tungsten carbide backup wafer. Nevertheless, these results are exceedingly promising. Thicker tungsten carbide backup wafers may allow the cutters to withstand higher forces and, therefore, larger wearflat areas before fracturing. This type of experimental TSP cutter shows significant potential for improving synthetic-diamond bit life in hard-rock drilling.

Optimization of Impregnated-Diamond Bits

A large number of laboratory drilling tests have been conducted in several rock types with various impregnated-diamond core bit designs (2-3/8 inch OD X 1-1/2 inch ID). An existing laboratory drilling machine was modified to increase its rotary speed capability to 1000 RPM. Weight-on-bit and drilling torque were measured for a variety of constant penetration rates and rotary speeds. A stereo microscope and scanning electron microscope (SEM) were used to examine experimental bits to study diamond distributions and wear patterns. A coordinate measuring machine (CMM) was used to measure bit wear and diamond exposures after drilling.

A baseline bit design was selected with nominal bit design parameters, including: diamond grade of SDA 100; diamond sizes of 25/30 and 35/40 mesh; diamond concentration of 100 (25% by volume); and matrix type 617. After establishing bit wear rates with the baseline design, changes were made in each of these design parameters to determine the effects of the changes on bit wear. Typical bit wear results are presented in Figure 14 for several of these design parameter changes. These results are the total wear of the bit in the axial direction after drilling 120 inches in each of three hard, abrasive rock types at a rotary speed of 750 RPM and a penetration rate of 20 ft/hr. Note the profound effect that changes in the design parameters can have on measured bit wear. These results are being used to determine the optimal design parameters with respect to bit performance and cost.

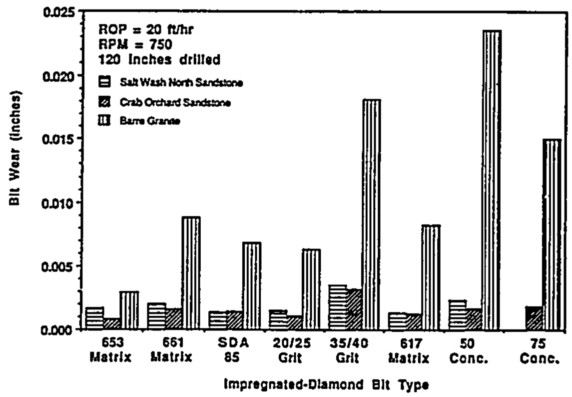

Figure 14 - Measured bit wear for various impregnated-diamond bit designs in three hard, abrasive rock types.

Mechanistic modeling of the impregnated-diamond cutting process is aimed at optimizing the matrix wear rate in various types of hard rock. Matrix wear must be rapid enough to provide adequate diamond exposure but not rapid enough to cause diamonds to be dislodged prematurely. It is therefore critical to understand the effects on matrix wear of several important parameters, such as: the distribution of penetrating stresses between the matrix and the diamond, which is a function of the diamond exposure and concentration; the relative hardness of the matrix and rock chips; the size of the rock chips; and the local velocity of the matrix, which is a function of the bit diameter and rotary speed. A model has been developed and compared with the experimental drilling results to define the relative wear resistance for various matrix types.

The model also allows prediction of important drilling parameters for a given bit design. Shown in Figure 15 is a comparison of the measured weight-on bit for the baseline bit design with that predicted by the model. Although the model does contain empirically-derived parameters, the excellent comparison with the experimental bit performance indicates that the model correctly simulates the essential cutting mechanisms involved. With further development and verification, the model should be useful in guiding the optimization of impregnated-diamond drill bit designs for any selected rock type.

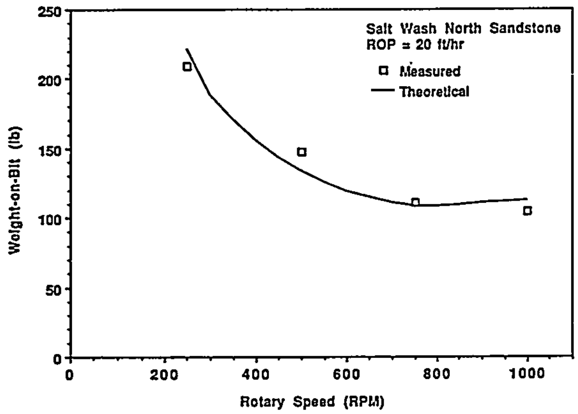

Figure 15 - Comparison of measured drilling performance with that predicted by the model developed for impregnated-diamond drill bits.

CONCLUSIONS

Steady progress has been made thus far in DOE's Advanced Synthetic-Diamond Drill Bit Program. Synthetic-diamond bit technology is already at a mature state, so major advances will not come easily. Furthermore, relatively modest funding levels for this program imply that progress will not be rapid. The work underway in the various projects is considered to be more evolutionary than revolutionary, with the intent of steadily improving bit performance and increasing the rock strengths that can be effectively drilled with synthetic-diamond drill bits. Nevertheless, the impact of such developments could be quite significant in that resources could be reached that are not economically accessible today.

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