Effects of Design and Processing Parameters on Performance of PDC Drag Cutters for Hard-Rock Drilling

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ABSTRACT

Sandia National Laboratories and U S Synthetic Corporation have jointly conducted a multifaceted, baseline experimental study to support the development of improved drag cutters for advanced drill bits. This study, which involved the production and laboratory testing of different nonstandard cutter lots, evaluated the influence of variations in selected design and processing parameters on cutter loads, wear, and durability in hard-rock environments. The focus was on drag-bit cutters that incorporated ultrahard PDC (Polycrystalline Diamond Compact) overlays (i.e., diamond tables) on tungsten carbide substrates. Parameter variations selected for the test cutters included changes in cutter geometry, material composition, and processing conditions. Geometric variables were the diamond-table thickness, the chamfer design for the cutter edge, and the diamond-table/substrate interface configuration. Material and processing variables for the diamond table were, respectively, the nominal diamond particle size and the pressure that was applied during cutter production. Complementary drop-impact, granite-log abrasion, linear cutting-force, and rotary drilling tests examined the response of cutters from each lot. A wide range of behavior was observed from lot to lot, and analyses of the test results assessed the relative merits of these lots, allowing identification of features contributing to improved cutter performance in hard-rock (e.g., geothermal) drilling applications.

Background

After the pioneering development and marketing of PDC cutters by General Electric (GE) in the 1970s, numerous companies initiated their own PDC cutter and drill-bit product lines. Since that time, Sandia National Laboratories has supported the drag-cutter and bit industries by conducting landmark research [Glowka, 1987; Finger and Glowka, 1989] to resolve problems with cutter design, manufacture, and utilization, thereby contributing very significantly to the advancement and commercialization of drag-bit technology [Falcone, 1995].

Drag bits have already achieved record-breaking performances in soft and medium-hardness formations [Perdue, 1999]. Furthermore, recent laboratory tests have shown superior performance of PDC bits relative to conventional rollercone bits for *hard-rock* drilling [Raymond, 2001]. On this basis, PDC bits could potentially drill at least twice as fast and last twice as long as roller bits in hard formations. Realization of this potential depends heavily on proper bit design and control, and on the complementary development of cutters with enhanced resistance to impact damage and thermal degradation, which are both accentuated in hard rock. The combined doubling of penetration rate and bit life will yield an estimated 15% reduction in cost for a typical geothermal well [Glowka, 1997]. Such an improvement in economy for hard-rock drilling will also substantially increase the number of candidate sites for geothermal energy production. These benefits are fully consistent with current U. S. Department of Energy (DOE) programmatic goals to (1) double the number of States with geothermal electric power facilities, (2) reduce the levelized cost of geothermal power generation, and (3) satisfy the electrical power or heat energy needs of more U.S. homes and businesses [Renner, et al., 2002].

Sandia coordinates a cooperative national laboratory/industry/university research and development effort to promote continued improvements in drag cutters and bits for more economical drilling in all formations. As part of this effort, Sandia maintains and applies its own unique, state-of-the-art expertise and capabilities that are specifically tailored to the analysis and laboratory testing of synthetic-diamond cutters and bits. Bit performance and wear are computationally simulated and new designs are generated using the Sandia-developed PDCWEAR code [Glowka, 1987]. Other codes available at Sandia have been applied to finite-element calculations of mechanical and thermal stress for cutters and bits. In-house experimental facilities include the Hard-Rock Drilling Facility (HRDF) and the Linear Cutter Test Facility (LCTF). The HRDF is a laboratory-scale drill rig that allows evaluations of cutter wear and dynamic loads in a realistic drilling environment with controllable operational parameters that include rotational rate (RPM), weight on bit (WOB), rate of penetration (ROP), and drillstring stiffness. The LCTF yields measurements of the orthogonal (triaxial) force components acting on cutters operated singly or multiply in a linear cutting mode. Data obtained from experiments on Sandia's HRDF and LCTF continue to provide a foundation for improved drag-cutting models [Yan, 1997; Johnson, et al., 2001].

Work Scope

For the activities described in this paper, Sandia partnered with U S Synthetic Corporation, a leading manufacturer of PDC products, to plan, manage, and execute a study to determine the effects of fundamental design and processing parameters on the performance and wear of PDC cutters. The parameters for study were mutually selected, and participation by U S Synthetic ensured the relevance of this study to current industry needs, interests, and capabilities. Cutter lots with specified nonproprietary parameter combinations were generated at U S Synthetic, then tested at both Sandia and U S Synthetic using laboratory facilities unique to each partner. The investigation of nonstandard cutter configurations distinguishes this work from earlier studies [e.g., Glowka, 1987], which were restricted to standard commercial products.

Sample Preparation

In total, U S Synthetic produced 12 lots of cutters for testing. All cutters had an outer diameter in the range of 0.528 - 0.530 inch, and a total length (diamond table plus substrate) in the range of 0.311 – 0.319 inch. These dimensions are characteristic of type '1308' production cutters (nominally 13.4-mm diameter x 8.0-mm thick), which are commonly used in commercial drag bits. Each lot consisted of about 20 identical cutters that were fabricated with the same unique combination of design and processing specifications. Geometric variables included the diamond-table thickness, the chamfer design, and the diamond-table/substrate interface configuration. Material and processing variables for the diamond table included, respectively, the nominal diamond particle size and the cubic-press line pressure that was maintained during the high-temperature cutter sintering operation. The lot-to-lot parameter variations for the present study included 4 diamond grain sizes, 2 sintering pressures, 4 diamond-table thicknesses, 3 edge-chamfer configurations, and 4 diamond-table/substrate interface patterns. Table 1 summarizes the specific parameter combinations for the individual cutter lots.

Table 1. PDC Cutter Specifications for Fundamental Parameter Studies.

Lot No.	Diamond Grain Size (μm)	Diamond-Table Thickness (in)	Chamfer Size	Interface Pattern	Cubic-Press Line Pressure (psi)
1	40	0.040	0.010 in x 45^o	Modified	6400
2	40	0.080	0.010 in x 45^o	Modified	6400
3	20	0.080	0.010 in x 45^o	Modified	6400
4	40	0.080	0.020 in x 45^o	Modified	6400
5	40	0.040	0.010 in x 45^o	Planar	6400
6	40	0.080	0.010 in x 45^o	Modified	5800
7	40	0.100	0.010 in x 45^o	Honeycomb	6400
8	40	0.160	0.010 in x 45^o	HM160	6400
9	40	0.080	0.015 in radius	Modified	6400
10	70	0.080	0.010 in x 45^o	Modified	6400
11	10	0.080	0.010 in x 45^o	Modified	6400
12	40	0.100	0.010 in x 45^o	Modified	6400

The nonplanar interface patterns called out in Table 1 are illustrated in Figure 1. For all interfaces, the specified diamond-table thickness corresponds to that produced at the cutter periphery, ignoring any deduction for the edge chamfer. Within each lot, only the six cutters to be used for cutting-force and drilling tests were actually manufactured with the chamfer size given in Table 1; the remaining fourteen cutters, which were slated for impact and abrasion tests, had a “sharp” (0.002 in x 45^o chamfer) edge.

Figure 1. Nonplanar interface configurations for cutter parameter studies.

Testing Protocol

Cutters from each lot were subjected to four types of testing: linear cutting-force and rotary drilling tests at Sandia, and drop-impact and granite-log abrasion tests at U S Synthetic.

The cutting-force tests involved triaxial dynamometer measurements of the load components acting on a single cutter while it produced linear cuts in Sierra White Granite (SWG) on the LCTF. For these tests, the cutter was rigidly mounted with a back-rake angle of 20^o and a side-rake angle of 0^o. Pairs of fresh cuts were made at cutting depths of 0.010, 0.020, 0.030, 0.040, 0.050, 0.060, 0.070, and 0.080 inch. For each cut, the force components were recorded continuously, then averaged to determine mean values of the penetration, drag, and side loads for a given depth of cut (DOC). These measurements were made for sharp (i.e., unworn) cutters, as well as test cutters that had sustained wear during drilling tests on the HRDF.

To acquire cutter wear data, a 3-cutter coring bit mounted in the HRDF drilled a series of holes that passed nearly through a 3-foot cube of SWG. Referring to Figure 2, cutters from a given lot were installed in the bit at the inside-gage, test (middle), and outside-gage locations, which were centered, respectively, at distances of 0.875, 1.125, and 1.375 inches from the bit centerline. For 0.528-inch diameter cutters, this arrangement yielded a borehole diameter of 3.278 inches and a core diameter of 1.222 inches. Simulations with PDCWEAR [Glowka, 1987] guided placement of the cutters so as to balance their individual contributions to the net side force on the bit; in the final design, the test and outside-gage cutters were angularly located on the bit face at 114^o and 276^o, respectively, relative to the inside-gage cutter at 0^o. All 3 cutters were set with the same projection above the bit face and a common back-rake angle of 20^o. The side-rake angle was 0^o for the test and inside-gage cutters, and 4.87^o for the outside-gage cutter. A rotational speed of 100 rpm and rate of penetration (ROP) of 30 ft/hr were maintained during drilling.

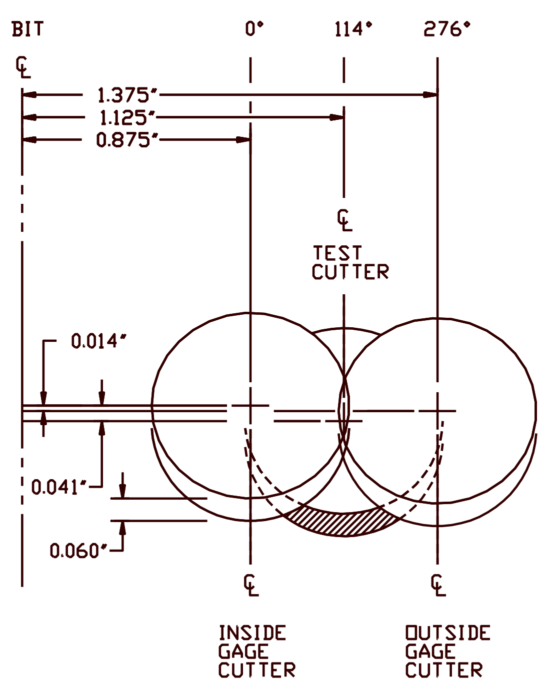

Figure 2. Cutter positions for successive rotations of the HRDF coring bit.

For the nominal drilling conditions, the DOC for one revolution of the bit was 0.060 inch, as indicated in Figure 2, which shows the cutter locations for two successive bit rotations. Looking at the bit face, during each counterclockwise rotation the outside gage cutter moved through an arc of 84^{o} to reach the initial angular location of the inside gage cutter, thereby advancing a distance of 0.014 inch into the rock. Similarly, the test cutter moved through an arc of 246^{o} to reach the same angular location, advancing 0.041 inch into the rock. The shaded portion of the test cutter shown in Figure 2 corresponds to the area that encountered rock that was not removed by the gage cutters. After each borehole, a videomicroscope was used to image and record the wear and damage sustained by the test cutter and gage cutters. In addition, image-processing software provided a measurement of the normal projected area of the test-cutter wearflat.

Abrasion resistance was measured by turning down the outer diameter of a log of Barrie Granite using a lathe that was equipped with a single PDC test cutter. The log was 10 inches long, and had an initial diameter of about 9.5 inches after truing. Using a water-based coolant, cutting was done at a surface speed of 400 ft/min, a cutter feed rate of 0.052 inch/revolution, and a DOC of 0.010 inch. The cutter back-rake angle was 15^{o}. Testing ended when the log diameter had been turned down to about 7 inches. Post-test measurements on the cutter and rock allowed determination of the "G ratio", which corresponded to the volumetric ratio of removed granite to lost test-cutter material.

Cutter impact resistance was determined using a drop-impact tester. For these tests, a cutter was rigidly mounted in a holder, then struck at a prescribed impact energy (20, 40, 60, 80, or 100 J) by a hardened (R_C 54 –56) steel plate that was attached to the lower surface of a falling dead weight. This process was repeated up to ten times for a given cutter at a fixed impact energy, and the final percentage of the diamond-table surface that had spalled was measured and recorded. If the spall percentage exceeded 30% of the cutter facial area after any drop, the cutter was deemed to have failed and no additional impacts were performed on that cutter. The cutter back-rake angle for these tests was 15^{o}, which corresponded to the angle between the plane of the cutter face and the normal to the striker plate. For each drop, an accelerometer attached to the dead weight provided time-resolved data for the impact loading history.

Experimental Results and Discussion

The initial series of cutting-force investigations measured the orthogonal penetration, drag, and side loads during linear cutting in SWG with one unworn PDC test cutter from each of the 12 lots. Figure 3 shows the time-averaged force components that were observed for a cutter from Lot 1 as it made two noninteracting cuts at each prescribed cutting depth. As expected, the 0^{o} setting for the side-rake angle yielded low levels of cutter side loading. For this cutter, the drag coefficient, which corresponds to the ratio of drag force to penetration force, remained relatively constant over the studied range of cutting depths. In fact, the mean drag coefficient only changed from 0.88 to 0.89 as the DOC increased from 0.010 to 0.080 inch. The present drag-coefficient results are consistent with earlier data obtained at Sandia for sharp, 0.50-inch diameter PDC cutters in SWG [Glowka, 1987].

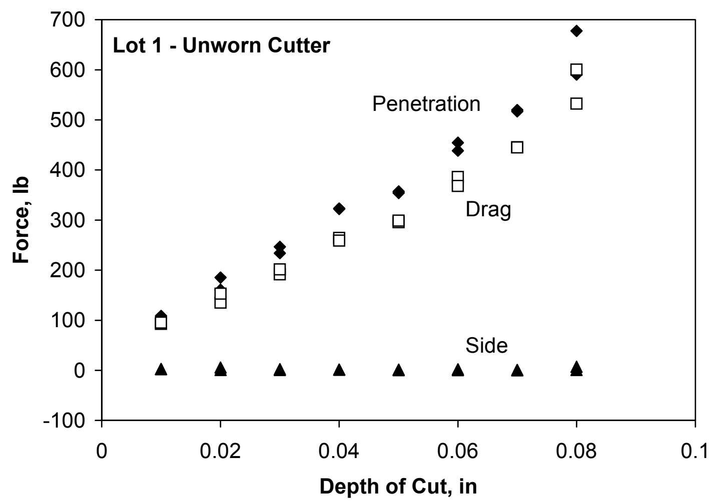

Figure 3. Linear cutting-force data for unworn cutter from Lot 1.

A follow-up series of linear force measurements was made with the worn cutters that had been used as the test cutters during HRDF drilling experiments. Figure 4 shows force data for the worn cutter from Lot 1, which had a final wearflat area (A_w) of 0.0160 in^2 after drilling 9 holes (each ~34.7 inches deep) in SWG. The drag and penetration forces for this cutter were much higher than those for the unworn cutter from the same lot. The drag coefficient for the worn cutter ranged from a minimum of 0.56 (0.020-inch DOC) to a maximum of 0.64 (0.070-inch DOC). The wear on this cutter reduced its projection from the cutter holder, limiting the clearance between the holder and the rock face; hence, testing was restricted to cutting depths no greater than 0.070 inch. The penetrating stress, which is the ratio of the measured penetrating force to the wearflat area, ranged from a minimum of 24.6 kpsi for a 0.010-inch DOC to a maximum of 80.2 kpsi for a 0.070-inch DOC. These values are somewhat larger than those observed previously for machine-ground and lab-worn PDC cutters operated in SWG [Glowka, 1987].

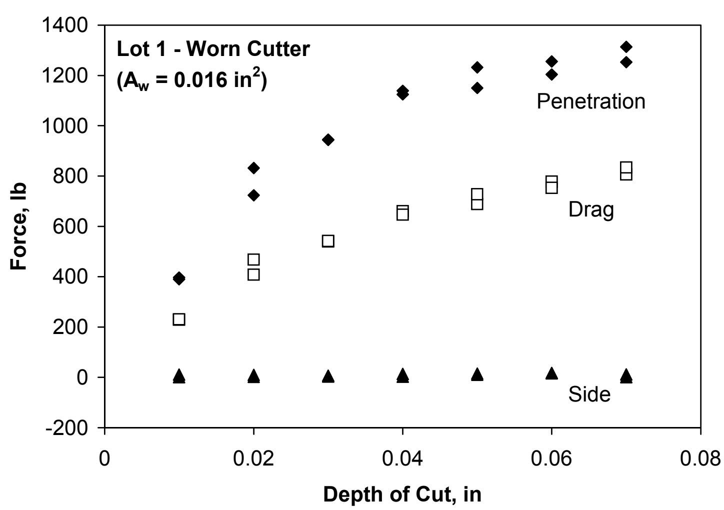

Figure 4. Linear cutting-force data for HRDF-worn test cutter from Lot 1.

Drilling tests in the HRDF were conducted with one set of 3 cutters from each of the 12 lots. Each set drilled a series of holes (each ~34.7 inches deep) in SWG. After every hole, a videomicroscope produced images documenting the wear and/or damage sustained by all three cutters (inside gage, outside gage, and test). In addition, the wearflat area for the test cutter was measured and recorded. Drilling with a given cutter set was terminated either when the test-cutter wearflat area reached a value of about 0.016 in^2 (10 mm^2), or when the magnitude(s) or oscillation amplitude(s) became excessive for the weight on bit (WOB) and/or torque on bit (TOB) required to maintain the nominal drilling conditions of 100 rpm and ROP = 30 ft/hr. The measured wearflat area for each test cutter is plotted in Figure 5 as a function of the hole number.

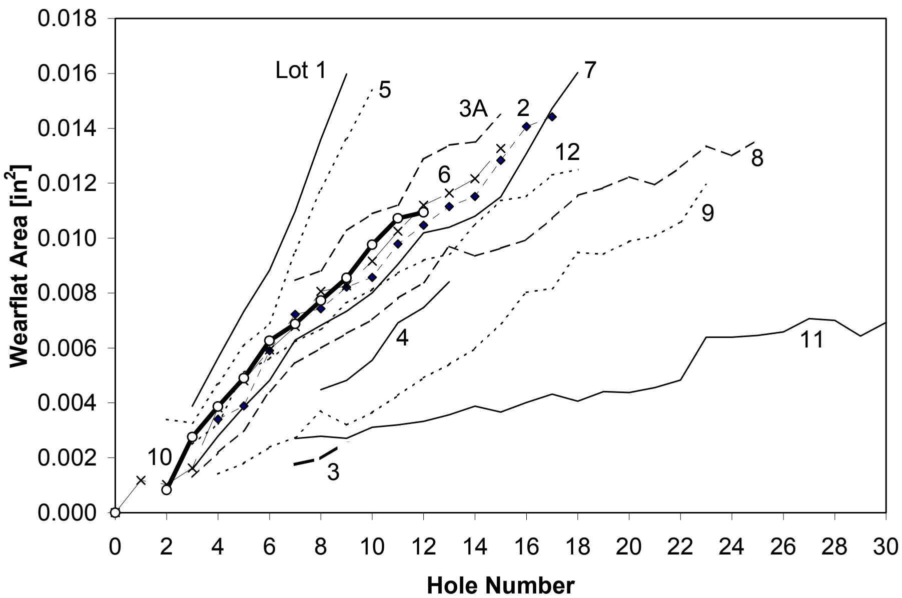

Figure 5. Wearflat data for test cutters used to drill Sierra White Granite in the HRDF.

As seen in Figure 5, a wide range of results was obtained for drilling tests on cutters from the 12 lots under investigation. The most rapid growth in wearflat area occurred for cutter Lots 1 and 5, which both had the smallest diamond-table thickness (0.040 inch) and an intermediate diamond grain size of 40 μm. By far the slowest growth in wearflat area and greatest longevity was observed for the test cutter from Lot 11, which had an intermediate diamond-table thickness (0.080 inch) and featured the smallest diamond grain size (10 μm). This small grain size was the parameter setting that most notably distinguished Lot 11 from the others; hence, it appears to be the key factor contributing to the superior drilling performance of this lot. Good performance was also obtained for Lot 8, which had the thickest diamond table (0.160 inch), and for Lot 9, which featured a unique initial edge chamfer of 0.015-inch radius. Drilling with the cutter set from Lot 3 was terminated early (hole 9) when the test cutter failed; hence, a second set of cutters (designated 3A) from this lot was tested to a hole count of 15.

The granite-log abrasion tests at U S Synthetic complemented the drilling tests described above. In total, 44 cutters were tested from the 12 lots. This corresponded to four cutters from each lot except Lots 2 and 4, which were manufactured concurrently according to the same recipe and whose abrasion samples were consequently identical since they had the same "sharp"

(0.002-inch x 45° chamfer) edge that was common to all cutters used for this round of tests. Hence 4, not 8, cutters were tested from the combined pool of sharp Lot 2 and Lot 4 cutters. Cutters from Lot 9 also shared the same recipe as Lots 2 and 4, making them nominally identical as well. However, the Lot 9 cutters were tested separately since they were fabricated in a later production run. For each cutter tested, the "G ratio" of rock removed to cutter material lost was determined. These "G ratios" were then averaged for the 4 cutters tested from each lot. The resultant data are shown in Table 2 where the entries are listed in order from the highest (best) to the lowest (worst) mean G ratio.

Table 2. Results of Granite-Log Abrasion Tests on Cutter Lots 1 through 12.

Lot No.	Average "G ratio"
11	9.14×10^6
12	3.15×10^6
10	2.01×10^6
3	1.87×10^6
7	1.82×10^6
8	1.75×10^6
9	1.66×10^6
2, 4	1.08×10^6
5	1.00×10^6
1	8.68×10^5
6	7.08×10^5

As in the case of the drilling tests, the fine-grained (10 µm) cutters from Lot 11 showed superior performance by a wide margin. Clearly the second-best performance was noted for Lot 12, which had an intermediate diamond grain size (40 µm) and featured the thickest diamond table on a "Modified" interface (see Figure 1). Cutters from Lot 6, which was produced with a lower cubic-press line pressure than the remaining lots (5800 vs. 6400 psi), exhibited the poorest abrasion resistance. As expected, the nominally identical cutters from Lots 2, 4, and 9 exhibited closely matching results.

Multiple cutters from each lot were subjected to drop-impact testing. For the same reasons noted above, cutters from Lots 2, 4, and 9 were also nominally identical for the impact tests, but Lot 9 samples were tested separately to avoid any question of lot-to-lot processing variations. The resultant data are summarized in Table 3, where the entries are listed in order from the lowest (best) to the highest (worst) failure rate. For those lots (2/4, 9, 10, and 11) that had no defined failures (i.e., >30% spallation of test-cutter facial area), the entries in Table 3 are made in order of increasing average spall area for the cutter face. Once again, the cutters from lots 2, 4, and 9 performed similarly. The high impact survival rate for cutters from Lot 10 with its large (70 µm) diamond grain size had been expected; conversely, the excellent performance of the Lot 11 cutters (10 µm grain size) had not been anticipated since smaller diamond grain size is typically employed to enhance abrasion resistance rather than fracture toughness. The Lot 8 cutters, which had a substantially thicker diamond table (0.160 inch) than any other samples, experienced the very highest failure rate under impact loading due to fracturing of the diamond table and, in some cases, shearing of the stepped HM160 substrate interface.

Table 3. Results of Drop-Impact Tests on Cutter Lots 1 through 12.

Lot No.	Average No. of Drops per Cutter	Average Energy per Drop (J)	Average Spall Area (% of Cutter Face)	Total No. of Failures (Facial Spall > 30%)	Total No. of Cutters Tested	Lot Failure Rate (%)
9	10	60	1.5	0	15	0
10	10	60	1.7	0	15	0
11	10	65	1.8	0	17	0
2, 4	10	60	2.7	0	20	0
5	10	63	6.1	1	18	5.56
12	9.7	64	7.5	1	17	5.88
1	10	63	7.1	1	16	6.25
7	9.6	63	9.1	1	16	6.25
6	10	60	14	1	10	10.0
3	9.7	63	8.7	2	18	11.1
8	8.5	62	33	6	19	31.6

To assess the overall relative merit of the *parameter combinations* selected for the 12 lots examined in this study, lot performance has been ranked for each of the three individual testing methods (HRDF drilling, granite-log abrasion, and drop impact), and an unweighted average of each lot's individual test rankings has been calculated. These rankings are reported in Table 4.

Table 4. Performance Ranking.

Lot No.	Drilling Rank	Abrasion Rank	Impact Rank	Overall Average Rank
1	12	11	8	10.3
2	6	8/9	4/5	6.3
3	10	4	11	8.3
4	8	8/9	4/5	7
5	11	10	6	9
6	7	12	10	9.7
7	5	5	9	6.3
8	3	6	12	7
9	2	7	1	3.3
10	9	3	2	4.7
11	1	1	3	1.7
12	4	2	7	4.3

From Table 4, Lot 11 had the best overall average ranking, followed by Lot 9. These rankings have been shown only as an illustration based on the present data set and the assumption that all three tests have equal significance in assessing cutter merit. The best assessment, of course, would ultimately come from observations made in a production-drilling environment.

Conclusions

The results of this investigation demonstrate that variations in design and processing parameters dramatically affect the drilling, abrasion, and impact performance of PDC cutters under conditions consistent with the penetration of hard (e.g., geothermal) rock formations. Instances of both performance enhancement and degradation have been observed as a consequence of adjustments in parameter specifications. Linear cutting-force data confirm and quantify large increases in drag and penetration force components as a consequence of drilling-induced wearflat growth. Wearflat measurements from the rotary drilling tests indicate a ratio exceeding 10 for the best versus worst wear rate. This result is consistent with measurements from the granite-log tests that show a factor of almost 13 between best and worst abrasion resistance. The drop-impact data evidence a wide range of design-dependent failure rates, with excellent impact resistance being demonstrated by several cutter formulations—including one that was expected to exhibit high wear resistance at the expense of limited fracture toughness.

The data summarized in this paper provide a useful basis for the future development of improved PDC cutters. To facilitate this development, Sandia and U S Synthetic are planning additional work that will (1) expand upon single-parameter performance trends identified during the present studies, and (2) identify and validate optimal parameter combinations for hard-rock cutters.

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