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IMPLICATIONS OF THERMAL WEAR PHENOMENA
FOR PDC BIT DESIGN AND OPERATION *

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ABSTRACT

Previous work has suggested that thermal phenomena can greatly accelerate the wear of polycrystalline diamond compact (PDC) drag cutters under certain conditions. In this paper, the implications of that finding for PDC bit design and operation are examined. An abrasive wear model for cutters is developed and applied to rotary drilling applications to demonstrate the significance of thermally-accelerated wear on bit life. Under conditions where thermal effects are not important, it is concluded that in order to maximize bit life, greater bit weights and lower rotary speeds are preferable over shallow cuts and high speeds. It is found that even under normal abrasive wear conditions, a PDC cutter develops a significant wearflat before one-half its useful life is expended, suggesting that PDC bits should be designed to operate effectively in the worn condition. A cutter placement criterion is presented for designing bits for equal cutter wear. Through analysis of new experimental data, a technique is developed for approximating cutter penetrating forces in the presence of cutter interactions on a bit face and for estimating relative cutter wear. A hypothetical bit designed for equal rock removal volume per cutter is examined to determine the relationship between the equal volume and equal wear criteria for cutter placement. The complex role of thermal wear phenomena in this relationship is also examined for the hypothetical bit in three different rock types.

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INTRODUCTION

The success of PDC drag bits in the petroleum drilling industry is well documented in the literature [1-4]. New performance records continue to be set as operating experience with these bits increases and new areas of application are found. Because of the inherently long life of PDC bits relative to roller cone bits under certain conditions, significant savings in total drilling costs are possible in some rock formations. The record published hole length drilled by a single PDC bit currently stands at over 6100 meters (20,000 feet) [1], and savings of over \$100k have been reported for a single PDC bit run [2].

Such remarkable results, however, are not universal. Many rock formations are apparently not suitable for conventional PDC bits [3,5]. The extreme stresses required to penetrate hard formations produce excessive frictional heating of the cutters, which leads to thermally-accelerated cutter wear [6,7]. Adverse downhole conditions such as abrasive rock formations, elevated temperatures, and dynamic bit loading complicate and intensify the problem.

The objective of Sandia's PDC bit research has been to determine the cause and effects of these phenomena on bit performance in order to extend the inherently rapid and efficient drag cutting process to harder rocks and more severe environments such as those found in geothermal drilling. Increased understanding of wear processes under these conditions should help to improve PDC bit life in soft and moderately hard formations as well.

REVIEW OF THERMAL WEAR PHENOMENA

In earlier work [6,8], we developed an analytical/numerical model for determining temperature distributions in stud-mounted PDC cutters under downhole conditions (see Figure 1 and Nomenclature for terminology). From this model, an equation for the mean cutter wearflat temperature was derived:

$$\bar{T}_w = T_{f1} + \frac{K_f F v f}{A_w} \left[1 + \frac{3\sqrt{\pi}}{4} f k_{hf} \left(\frac{v}{\alpha_f L} \right)^{1/2} \right]^{-1} \quad (1)$$

By applying this equation to the results of cutter wear measurements under controlled conditions, a correlation was obtained between cutter wear (based on volume) and mean wearflat temperature. It was found that at wearflat temperatures above 350°C (660°F), the wear rate increases rapidly from that obtained at lower temperatures, and the cutter quickly dulls.

This finding is consistent with that reported in the literature [9,10] for cemented carbides. The hardness of WC-Co (tungsten carbide-cobalt) drops more rapidly with temperature than that of quartz, the principal abrasive constituent in rock. As a result, the hardness of the two materials becomes comparable at temperatures above 300-400°C, resulting in greatly increased WC-Co wear at the wearflat due to preferential cobalt removal and fracturing of the WC skeletal structure. Since the polycrystalline diamond compact layer on a PDC cutter is supported by the WC-Co compact and stud, the diamond layer at the wearflat is easily fractured if the WC-Co behind it

is worn away. It is, therefore, not unreasonable to expect a PDC cutter as a whole to exhibit thermally-accelerated wear similar to that of WC-Co alone.

In addition to a general softening of PDC cutter materials with temperature, it was also found through numerical modeling [7] that unfavorable stresses arise in PDC cutters under downhole conditions that produce wearflat temperatures above 350°C. Under steady-state water or mud drilling conditions, large thermal gradients and a thermal expansion coefficient mismatch at the diamond/WC-Co interface combine to produce significant compressive and tensile stresses in various parts of the cutter. Compressive stresses in the wearflat region can reach levels sufficient to cause plastic deformation of the WC-Co at temperatures between 350 and 750°C. This leads to the development of voids in the composite microstructure that serve as crack initiation sites. Along the diamond face, thermal effects act to impose tensile stresses or to at least significantly reduce any residual compressive stresses that may be present in the diamond composite after sintering. This could lead to increased fracturing of the diamond on both microscopic and macroscopic scales.

If a PDC bit is suddenly pulled off-bottom, or if bit bounce occurs, the hot cutter wearflats are susceptible to thermal shock as a result of rapid cooling by water or drilling mud circulation. The unfavorable temperature gradients that develop, combined with the sudden removal of all compressive stresses due to bit weight, cause the wearflat region to undergo tension. Any microscopic fractures that develop as a result of abrasion or plastic deformation are easily propagated in the presence of the tensile stresses to form wear particles. Analysis shows that thermal shock can be prevented and the cutter wearflat maintained in compression by taking precautions to prevent bit bounce and by reducing bit weight slowly whenever lifting off-bottom.

Numerical results obtained with reduced cutter cooling coefficients suggest that when air is used as the drilling fluid, tensile stresses throughout the cutter are greatly increased. Furthermore, the wearflat region undergoes tension due to thermal effects, even under constant applied bit weight. The increased tensile stresses explain why air cooling is detrimental to PDC bit life during hard-rock drilling [5].

Under conditions producing wearflat temperatures below 350°C, compressive and tensile stresses throughout the cutter are significantly reduced from those described above. This suggests that the thermally-accelerated wear that occurs above 350°C is somewhat inherent to the materials used in PDC cutters. Some microstructural design changes may be possible to improve the inherent wear characteristics of these materials; however, the existing materials are already the products of extensive research and optimization, so further improvement will not come easily [11,12]. For the present study, it will therefore be assumed that 350°C is the highest mean wearflat temperature that can be tolerated in practice. By inserting this value for $\bar{T}_w$ and solving Eq. 1 for F/A_w , we arrive at an expression for determining the critical penetrating (normal) stress between the cutter and the rock:

$$\sigma_{cr} = \frac{(350^\circ\text{C} - T_{f1})}{K_f v f} \left[1 + \frac{3\sqrt{\pi}}{4} f k_{hf} \left(\frac{v}{\alpha_f L} \right)^{1/2} \right] \quad (2a)$$

Under conditions leading to penetrating stresses greater than σ_{cr} , the wearflat temperature exceeds 350°C and thermally-accelerated wear occurs. We must therefore ensure that during drilling,

$$\sigma = F/A_w < \sigma_{cr} \quad (2b)$$

for each cutter on a PDC bit. In this paper, the implications of this restriction on bit design and operation are examined.

PDC CUTTER WEAR CONSIDERATIONS

Drag Cutter Wear Models

The visible effect of wear on a drag cutter is the development and growth of the wearflat area. Its effect on cutter performance is an increase in the penetrating force required to cut to a given depth [13].

Data obtained during the course of this study illustrate the effect with a PDC cutter, as seen in Figure 2. It is seen that cutter wear has a tremendous effect on the penetrating force required to cut hard rock to a given depth. These data suggest that it is the penetrating stress rather than merely the force that controls the depth of cut in a given rock type. This conclusion is supported by data in the drag bit cutting literature [14-18]. For a constant depth of cut or bit penetration rate, the penetrating stress remains relatively constant with cutter wear once a wearflat has been established. With sharp cutters, the calculated penetrating stress F/A_w tends to infinity. In reality, crushing of the rock beneath the sharp tip probably acts to redistribute cutter stresses over a larger area, resulting in an effective wearflat area of finite value. The smaller the wearflat area, the greater the influence of this effect will be and the greater the departure in calculated penetrating stress from the values obtained with larger wearflats at the same depth of cut.

Because cutter wear so greatly affects bit performance, it is of interest to examine the theoretical growth of the wearflat as drilling proceeds. Experimental data on abrasive wear of drag cutters are available in the literature [14-17] for conditions under which thermal effects are not important. These data indicate that the volumetric wear of a cutter per unit cutting length is related to the penetrating force in one of three ways:

$$\frac{dV_w}{dl} = C_1 F. \quad (3a)$$

$$\frac{dV_w}{dl} = C_2 \frac{F}{A_w}. \quad (3b)$$

and, for the special case of constant penetration rate or depth of cut,

$$\frac{dV_w}{dl} = C_3. \quad (3c)$$

Here the constants C_i are, in general, strong functions of cutter material and rock types.

A physical model for Eq. 3a can be developed by assuming that the depth of wear into the surface of the cutter material per unit cutting distance is proportional to the contact or penetrating stress:

$$\frac{d\delta_w}{dl} \propto \frac{F}{A_w}.$$

Using the chain rule of differentiation, plus the fact that $dV_w/d\delta_w = A_w$, we obtain the result given in Eq. 3a. This model is intuitively satisfying because two cutters of equal wearflat area A_w , each under a penetrating force F , would have a combined wear rate equal to that of a single cutter with wearflat area $2A_w$ under a penetrating force $2F$. Previous work [14,15] with WC-Co cutters has shown, in fact, that enlarging the wearflat by increasing the width of the tool for a given wearflat length results in an approximately proportional increase in both penetrating force and volumetric wear rate for a given depth of cut, which agrees with Eq. 3a.

The same work has shown, however, that if the wearflat area is enlarged by increasing its length for a constant tool width, then the relation shown in Eq. 3b is followed. It was postulated that this is due to a reduction in the relative abrasiveness of loose rock particles as the wearflat length is increased. This may be a good assumption in view of the fact that loose rock particles that pass between the cutter and the rock probably become more broken with a longer wearflat, as they are subjected to significant crushing pressures for a longer period of time. Those particles would then be less abrasive on the average, and the average depth of wear over the larger wearflat would be reduced. A mathematical model may be obtained by assuming that the depth of wear per unit cutting distance is proportional to the penetrating stress and inversely proportional to the wearflat area; thus

$$\frac{d\delta_w}{dl} \propto \frac{F/A_w}{A_w}.$$

This can be converted to Eq. 3b, which agrees with the experimental observations described above.

Wear behavior according to Eq. 3c is a special case of that under Eq. 3b. Several studies, e.g. [10], have found that after an initially high rate, a bit experiences approximately constant dV_w/dl over the hole length if the penetration rate is maintained constant by increasing the penetrating force to maintain constant stress as the wearflat area grows with wear. It is thus seen that Eqs. 3b and 3c are equivalent in the constant penetration rate case.

Limited PDC cutter wear data are available in the open literature [16,17]. Analysis of these data has shown that for conditions producing wearflat temperatures less than 350°C , the volumetric wear rate dV_w/dl was relatively low and constant (10^{-11} to $10^{-10} \text{ cm}^3/\text{cm}$), but it increased rapidly by as much as two orders of magnitude under higher frictional temperatures [6]. This indicates that the wear model of Eq. 3c was followed in the low-temperature tests,

which is the conclusion reached in Ref. 16. Since these data were obtained at constant depth of cut, the model of Eq. 3b should also be applicable. Further analysis of the data indicates that although there is considerable scatter typical of rock-cutting data, penetrating stresses remained relatively constant (within $\pm 27\%$ of median value) as the wearflat areas quadrupled in size due to wear. The result of this analysis is that the model of Eq. 3b describes the wear behavior as well as that of Eq. 3c, as expected.

Although there is less correlation when the experimental data are plotted in the form suggested by Eq. 3a, there is still considerable uncertainty relative to an appropriate wear model for these cutters. It is probable that cutters follow some behavior between that described by Eqs. 3a and 3b since both the length and the width of the wearflat increase as the wearflat area grows. We can therefore write a general form of the wear equation as

$$\frac{dV_w}{dl} = C_4 \frac{F}{A_w n^4} \quad (4)$$

where $0 < n^4 \leq 1$, depending on the form of the equation chosen.

Application to Rotary Drilling

The availability of a cutter wear model allows us to determine the wear characteristics for a given cutter and bit geometry. As shown in Appendix A, the length of cut for an individual cutter at radial position r on a bit face is given by the equation,

$$l = \frac{2\pi r N}{R} l_h \quad (5)$$

where l_h is the length of hole drilled by the bit. Equation 4 may be integrated to determine the wear volume after drilling a given length of hole:

$$V_w = \int \frac{dV_w}{dl} \frac{dl}{dl_h} dl_h \quad (6)$$

A more convenient measure of wear than the wear volume is the wearflat length L . As shown in Appendix A, the relationship between these two variables is a function of cutter geometry and for the 20° back-rake, stud mounted PDC cutter considered in this paper is given approximately by the equation

$$L = 2.4 V_w^{0.4} \quad (7)$$

Differentiating Eq. 5 and combining with Eqs. 6 and 7, we get the result

$$L = 2.4 \left[2\pi r \int \frac{N}{R} \frac{dV_w}{dl} dl_h \right]^{0.4} \quad (8)$$

We can now determine how the wearflat area grows as drilling proceeds. For a constant penetration rate and rotary speed over the hole length, the cutter penetrating stresses are approximately constant, as discussed earlier. If we accept the wear model given by Eq. 3b, then dV_w/dl is also constant over the hole length. Equation 8 then becomes

$$L = 2.4 \left[2\pi r \frac{N}{R} \frac{dV_w}{dl} l_h \right]^{0.4} \quad (9)$$

To illustrate the implications of this equation, we assume a radial cutter position near the periphery of a 22.2 cm (8-3/4 inch) PDC bit, drilling at a feed rate R/N of 0.10 cm/rev (0.040 inch/rev). This corresponds, for example, to a penetration rate of 6.1 m/hr (20 ft/hr) at 100 RPM. The results are shown in Figure 3 for a range of volumetric wear rates measured against hard, abrasive sandstones in the controlled experiments of Refs. 16 and 17.

Examination of Figure 3 allows us to determine the wearflat length L after any given length of hole drilled. If we can define some wearflat length L_{max} at which a cutter is considered "worn out", we can determine the bit life. Although no rigorous determination of L_{max} is available, operating experience in moderately hard rock [19] suggests that L_{max} is approximately 0.5 cm (0.2 inch). Volumetric wear rates of 10^{-11} to 10^{-10} cm³/cm are typical of those measured under conditions where temperature effects are insignificant. Note that at these wear rates, the cutter under consideration becomes worn out only after the bit has drilled over 3000 m (10,000 ft). If at some point conditions become such that thermally-accelerated wear occurs, then wear rates of 10^{-9} to 10^{-8} cm³/cm are possible. At such rates, a new bit would become worn out in only 30 to 300 m (100 to 1000 feet). The impact of thermally-accelerated cutter wear on bit life and, therefore, drilling economics is clearly illustrated. At lower feed rates, bit life is reduced, as seen in Eq. 9. If, for example, drilling conditions are such that the ratio R/N is only one-half that considered in Figure 3, then the bit becomes worn out after drilling only 76% of the hole lengths described above.

Another feature of Figure 3 is the rapid growth in wearflat length when the cutter is sharp. This is in agreement with results obtained with WC-Co drag bits under constant penetration rate conditions [10,13]. Note that a "moderately worn" configuration is obtained after only about 50% of the total bit life is expended. Under this configuration, the wearflat extends across the entire WC-Co compact to which the diamond layer is attached [$L=0.38$ cm (0.15 inch)]. The bit thus spends at least one-half of its useful life in at least a moderately worn condition.

The implication of this result is that PDC bits should be designed and operated such that good bit performance is achieved in the worn condition. Any bit so designed will inherently have better performance when it is sharp. Since thermally-accelerated wear effects can assume greater

importance as the wearflat area grows [8], the range of allowable design options and operating conditions is smaller for a worn bit. In the next section, we will examine the effects of the wear models discussed above on PDC bit design.

PDC CUTTER PLACEMENT CRITERIA

In this section, we examine three criteria for determining the optimal cutter distribution on a PDC bit face.

Equal Cutter Wear

The availability of a wear model suggests that a PDC bit might be designed so that each cutter on the bit face or within a given region on the bit face wears at the same rate. Such a design would maximize the life of the bit as a whole, since no single cutter would be stressed above the limit at which thermally accelerated wear occurs. It would also optimize the use of expensive cutter materials, particularly for matrix-mounted PDC bits in which the cutters cannot be easily replaced during bit reconditioning.

The quantity we wish to make uniform across the bit face is the volumetric cutter wear per unit hole length. Using Eqs. 4 and 5, together with the chain rule of differentiation, gives the desired criterion:

$$\frac{dV_w}{dl_h} = \frac{2\pi r N C_4 F}{R A_w^{n_4}} = \text{constant for each cutter.} \quad (10)$$

This equation is applicable to all cutters whose wearflat temperatures are less than 350°C. At higher temperatures, thermally-accelerated wear occurs and Eq. 10 is not valid. In this higher regime, wear becomes more unpredictable, and wear across the cutters becomes non-uniform due to temperature gradients across the wearflats.

The design penetrating force for each cutter according to the equal wear criterion is obtained by solving Eq. 10:

$$F = \frac{R A_w^{n_4}}{2\pi r N C_4} \frac{dV_w}{dl_h} \quad (11a)$$

where the limitation

$$F < \sigma_{cr} A_w \quad (11b)$$

ensures that thermally-accelerated wear will not occur.

Design optimization according to this criterion would consist of placing cutters at radial positions on the bit face such that the actual penetrating force approximates the design penetrating force for each cutter. Since the actual penetrating force for each cutter is a function of its depth of cut, speed, and interaction with adjacent cutters, it is apparent that design according to this criterion is not a simple task. In concept, however, such a design appears possible because a bit's circular face allows cutter density to be increased with radial position r in order to reduce penetrating forces as required by Eqs. 11a and 11b.

Equal Cutting Power

The product of the drill string torque and rotary speed during drilling is the total drilling power. This quantity for a PDC bit is closely related to the cutting power of the individual cutters. A cutter placement criterion suggested in the past [20] is for uniform cutting power across the bit face:

$$P = F_d v = F_d 2\pi r N = \text{constant for each cutter.} \quad (12)$$

We define the drag coefficient of the cutter as

$$\mu_d = F_d / F \quad (13)$$

Combining the above equations provides a relation for determining the design penetrating force for each cutter under the equal cutting power criterion:

$$F = \frac{P}{2\pi r N \mu_d} \quad (14)$$

This criterion is examined further in a later section.

Equal Rock Removal Volume

This is perhaps the most widely known cutter placement criterion due to the general availability of the STRATAPAX computer code [21] for calculating the volume of rock removed by each cutter in a given bit design and optimizing the radial placement of the cutters to equalize those volumes. Design under this criterion places cutters such that

$$V_r = \text{constant for each cutter.} \quad (15)$$

A typical cross-sectional area of cut for a moderately worn cutter on a bit face is shown in Figure 4. Each cutter travels in its own unique helical path as the bit is rotated and advanced along the hole length. The cross-sectional area of cut depends on the feed rate R/N of the bit and the distribution of all cutters within a given radial range of the cutter under consideration. The relative circumferential positions of such "adjacent" cutters determines the distance advanced by the bit between the times of the adjacent cuts and the cut of interest. The size and shape of the cross-sectional area of cut is thus a function of bit design. The rock removal volume is related to the cross-sectional area by the approximate relation:

$$V_r = 2\pi r A_r \quad (16)$$

No force considerations are necessary to optimize according to the equal volume criterion; however, it is of interest to examine the relationship between rock volume and cutter forces in order to determine the general relationship among the three criteria considered in this paper. Because of the complex nature of cutter interaction, experiments

were deemed necessary to provide guidance in this area.

EXPERIMENTAL DATA AND ANALYSIS

Laboratory measurements of cutter forces under different cutting patterns in different rocks were undertaken as described in Appendix B. A large milling machine was used to measure penetrating (vertical), drag (parallel to cut), and side forces while machining linear paths in rock samples with single PDC cutters under atmospheric conditions.

Three rock types were used in these tests: Berea sandstone, $S = 49.0$ MPa (7.1 kpsi); Tennessee marble, $S = 123$ MPa (17.8 kpsi); and Sierra White granite, $S = 48$ MPa (21.5 kpsi). In addition to rock type, test variables included depth of cut and lateral distance to previous adjacent cuts. All tests were conducted with "moderately worn", 20° back-rake, stud-mounted PDC cutters as described earlier. The cutting speed in all tests was 5.6 cm/sec (2.2 in/sec), the maximum table speed of the milling machine.

Cuts With No Interaction

A series of tests were performed to determine how close adjacent cuts can be before they affect the penetrating force of the cut under consideration. It was found for all three rocks that as long as adjacent cuts were farther away than the width of the cut, no effects are discernable. The conclusion was reached that penetrating forces are affected only by those cutters that actually reduce the cross-sectional area of the cut under consideration.

For the no-interaction configuration, the effect of depth of cut δ on penetrating force F was determined for all three rock types. The forces were divided by the wearflat area A_w for each test, and the results are shown in Figures 5 and 6 in terms of the penetrating stress, F/A_w , between the cutter and the rock. The solid curves are plots of the equation

$$(17) \quad \delta = C_5 \left(\frac{F}{A_w S_c} \right)^{n_5} \quad (17)$$

where C_5 and n_5 were determined for each rock type by a least-squares fit of the data in log-log space. These parameters are listed in Table I. Also listed are correlations constants for data available in the literature [20] on hard-rock cutting with worn drag cutters.

Note that the exponent n_5 for each rock type is greater than 1, illustrating the efficiency, with respect to penetrating stress, of deep cuts versus shallow ones. The literature on drag cutting [22-24] indicate that at shallow depths of cut, grinding of the rock surface is the predominant cutting mechanism. With deeper cuts, the more efficient mechanism of rock chipping dominates, and small increases in penetrating stress produce large increases in depth of cut. It has been concluded that the grinding regime should be avoided because of a disproportionately high wear rate per unit hole length. This agrees with Eq. 9, where it is shown earlier that the use of larger feed rates R/N reduces the wearflat growth with respect to hole length.

The form of correlations obtained with Eq. 17 has further implications for bit wear. The effective

depth of cut for each cutter on a bit is directly proportional to the bit feed rate. By combining Eq. 17 with Eq. 4, the quantity inside the integral of Eq. 8 becomes

$$(18) \quad \frac{N}{R} \frac{dV_w}{dl} \propto \left(\frac{1}{\delta} \right)^{1-1/n_5} \quad (18)$$

Since n_5 has been found to be great than 1 for all available single cutter data, the conclusion is reached that to maximize bit life, the depth of cut and therefore the penetrating force on each cutter should be maximized. Of course, since temperature also rises with penetrating force (see Eq. 1), this conclusion is valid only up to the point where thermally-accelerated wear begins. The consequence of this finding is that for maximum bit life, the lowest rotary speed and highest bit weight possible should be used, within the constraint that the bit weight should not exceed the critical level at which thermal effects become important.

Under conditions where thermal wear effects are generally not encountered, other constraints on bit weight may apply. For example, bottomhole cleaning problems in certain formations may cause the penetration rate to fail to respond to bit weight in the manner suggested by the large exponents, n_5 . For practical purposes, it may be possible to maximize bit life downhole by test drilling at several combinations of bit weight, W , and rotary speed, N , while measuring penetration rate, R . The conditions under which the maximum value of feed rate, R/N , is obtained are those under which the maximum bit life should be achieved. Since the penetration rate will change with cutter wear, it may be important to conduct small test series periodically throughout a bit run in order to adjust drilling variables to suit the condition of the bit and maximize its life.

Numerous studies with sharp and worn WC-Co drag bits have found a linear relationship between penetrating force and penetration rate in the rock chipping regime, with the data extrapolating back to a non-zero penetrating force at zero depth of cut [15]. This threshold force was found to increase in magnitude with cutter wear and uniaxial compressive strength [13].

With very few exceptions, the published works in this field have failed to measure and report wearflat areas corresponding to the measured forces. In previous work [25], we found that the small amount of available data [18,20] obtained with measured wearflats could be correlated in an interesting way in terms of penetrating stress. It was found that the data extrapolate to a zero depth of cut at a penetrating stress near the uniaxial compressive strength of the rock.

The new data presented in Figures 5 and 6 for the most part exhibit the same behavior. These data include depths of cut that are much smaller than those of the previous data and probably represent the transition from the grinding to the rock chipping regime. It is difficult to determine which data should be considered indicative of grinding and therefore excluded from the process of determining a correlation for the chipping regime. Note in general, however, that the penetrating stress apparently must exceed the uniaxial compressive strength of each rock before significant penetration indicative of chipping occurs.

In the case of Berea sandstone, some departure from this conclusion is evident, as significant penetration begins at stresses somewhat below the compressive strength of that rock. Cutting mechanisms may be different here from those of the other, much harder rocks considered. A more gradual and delayed transition from grinding to chipping would be consistent with the more plastic failure behavior exhibited by lower strength rocks.

The concept of a threshold penetrating stress for rock chipping in hard rocks suggests a correlation of the form,

$$\delta = C_6 \left(\frac{F}{A_w S_c} - 1 \right)^{n_6} \quad (19)$$

Such correlations have been obtained for the hard rocks tested here by considering only those data for which $\delta > 0.05$ cm (0.020 inch). The resulting values of C_6 and n_6 are listed in Table I. The dashed curves of Figures 5 and 6 represent this equation for each of the rocks shown.

Note that for the hard rocks ($S > 100$ MPa) shown in Table I, the constants C_5 and C_6 and the exponents n_5 and n_6 are remarkably similar among the three data sets. The data of Ref. 18 were obtained with a rock type twice as hard and wearflats ten times as large as those considered in this paper, yet when the data are normalized as shown, the behavior is very similar. This suggests that Eqs. 17 and 18 may be somewhat universal correlations, at least for hard rocks. Of course, further testing will be necessary to establish this with confidence. In particular, the effects of downhole stresses must be considered. This is discussed in more detail in a later section.

In addition to penetrating forces, drag and side forces were also measured in the tests performed in the current study. For cuts having no interaction with adjacent cuts, side forces were negligible. Drag forces, on the other hand, were significant, underscoring the fact that PDC bits are high-torque drilling tools. The cutter drag coefficient, as defined earlier, is plotted for all three rock types in Figure 7. Note that for a given rock type, the relation between the penetrating and drag force is relatively independent of depth of cut. This will be further discussed when the results for cuts with interaction are presented.

Cuts With Interaction

In order to simulate a typical bottomhole cutting pattern for a cutter on a PDC bit, tests were also made in the presence of previous adjacent cuts. The general configuration is shown in Figure 8, where the cut of interest is in the center. The depth of this cut was set at 0.2 cm (0.080 inch) for this test series, with the depth of adjacent cuts set at one-half that value. The distance to adjacent cuts, d , was varied from 0.127 cm (0.05 inch) to 1.27 cm (0.5 inch) in two patterns: a symmetric pattern with an adjacent cut on each side of the center cut, and an asymmetric pattern with only one adjacent cut. These patterns simulate typical patterns on a bit advancing at a feed rate of 0.2 cm/rev (0.080 in/rev) when radially adjacent cutters are circumferentially located on the opposite side of the bit. The results obtained for Sierra White granite and Berea sandstone are shown in Figure 9.

The upper and lower dashed lines for each rock type in Figure 9 represent the mean penetrating forces measured for 0.1 cm (0.040 inch) and 0.2 cm (0.080 inch) cuts, respectively, when no interaction with adjacent cuts exists. Note that most of the data for both rocks fall within the respective bands described by the dashed lines. This is reasonable, because at small cutter spacing, the geometrical configuration for the center cutter approaches that of a single 0.10 cm (0.040 inch) cut with no interaction; at large spacing, it approaches that of a single 0.2 cm (0.080 inch) cut with no interaction.

These results suggest a relatively simple model for estimating penetrating forces for arbitrary cutter placement patterns. The penetrating stress required for a drag cut has been shown to increase with the depth of cutter penetration into the rock from the surface. This is probably related to the distance that fractures must travel from the cutting edge, through the rock, and to the free surface in order to form a rock chip in front of the cutter. The greater the depth of cut, the greater that distance becomes. As shown in Figure 10, cutter interaction at a rotary bit face causes the depth of cut to vary over the width of the theoretical cross-sectional area of rock removed by a cutter. Thus the distance that fractures ahead of the cutter must travel to reach the free surface varies over the cut's width. As a result, it is reasonable to assume that cutter forces required to propagate those fractures is determined by some effective depth of cut. For simplicity, we assume that the effective depth of cut is approximated by the mean value of $\delta(z)$ across the cut:

$$\delta_e = \frac{1}{w_0} \int_0^w \delta(z) dz \quad (20)$$

Substituting δ_e into Eq. 17 gives the result,

$$F = A_w S_c (\delta_e / C_5)^{1/n_5} \quad (21)$$

The algorithm used by the STRATAPAX code to compute cross-sectional areas fortuitously computes quantities that can be used to calculate $\delta(z)$ for each cutter across a bit face. In this study, the code was modified to compute the effective depths of cut according to Eq. 20. In addition, the code was generalized to allow cutter geometries to be changed by wear. Algorithms have been installed to modify the elliptical cutting edge of each cutter with a flat wearflat of a given width specified by the user. Such wearflats affect the cross-sectional area and effective depth of cut.

The modified code was used to compute δ_e for the cutting patterns used in the tests reported in Figure 9. The results are plotted in Figure 11 against the measured penetrating forces for corresponding tests. Equation 21 is also plotted for both rock types, using the measured constants listed in Table I. The agreement is excellent, suggesting that the mean depth of cut is a good measure of the effective depth that allows the no-interaction correlations to be used when cutter interaction exists. Using this model, we can now compute penetrating forces for arbitrary cutter placement, thereby enabling us to use the equal wear criterion for bit design.

Drag forces measured during the cuts made with interaction were divided by the corresponding penetrating forces. The results were almost identical to those obtained with the no-interaction cuts (Figure 7). In sandstone, μ_d ranged between 0.92 and 0.96; in granite, between 0.58 and 0.65. These results indicate that the drag force is directly related to penetrating force on a PDC bit and is not affected by the effective depth of cut. This implies a constant value of μ_d for all cutters across the bit face; as a result Eq. 14 shows that the design penetrating force under the equal cutting power criterion is inversely proportional to the cutter radial position. A bit designed according to the equal wear criterion will therefore also satisfy the equal cutting power criterion.

This should be regarded as a tentative conclusion since the data in this study were obtained at very low cutting speeds. Some evidence does exist for both PDC [26] and WC-Co [27] drag cutters that penetrating force increases slightly with cutting speed, whereas drag force is relatively independent of speed. The ratio μ_d is then likely to be a function of cutting speed and therefore radial position on the bit face.

USE OF EQUAL WEAR CRITERION IN BIT DESIGN

Development of specific bit designs based upon the equal wear criterion is beyond the scope of this paper; however, some of the general effects that this criterion would have on design are examined in this section. This is done by considering a hypothetical PDC bit, optimized using the modified cutter placement code for equal volume removal per cutter. The wear characteristics for such a bit design are determined according to the models described above. This provides a clear indication of how bit design may differ under the equal wear criterion.

For illustration purposes, we consider a 22.2 cm (8-3/4 inch) bit having 40 cutters arranged in the spiral patterns shown in Figure 12. In order to protect the bit gage, cutter redundancy was provided by placing the outermost cutter in each spiral arm at the same radial location [$r=10.45$ cm (4.115 inches)]. A flat bit profile is assumed, meaning that all cutters rotate in the same plane. Moderately worn cutters, as previously described, were used in the calculations.

The modified computer code was used to optimize the radial placement of cutters so that rock cutting volumes were approximately equalized. The innermost 4 cutters on the bit were excluded from the optimization process because of their small radial locations [< 2.5 cm (1.0 inch)]. In order to illustrate the effects of cutter redundancy, a change was made to the optimized design prior to performing further calculations. Cutter 40 was moved from near the center of the bit to the periphery in order to increase local cutter density and thereby help relieve cutters 32 and 36.

To simplify comparisons, all results were divided by the corresponding results for a reference cutter, number 4, located at a radial position of 2.604 cm (1.025 inches). The absolute quantities computed for cutter 4 are listed in Table II. Results have been obtained for bit feed rates of 0.025 to 0.25 cm/rev (0.01 to 0.1 inch/rev). The detailed results are presented only for 0.15 cm/rev (0.060 inch/rev), but they are similar to those

obtained for all feed rates. A 0.15 cm/rev feed rate corresponds, for example, to a penetration rate of 9 m/hr (30 ft/hr) at 100 RPM.

The relative rock removal volumes for each cutter are shown in Figure 13, where cutter radial position increases with cutter number. Note that rock volumes for most cutters are very close to that of the reference cutter, number 4 (relative $V_r=1.0$). The design modification previously mentioned is seen to have a significant effect on cutters 32 and 36, which have 34% and 46% reductions in cutting volume, respectively, due to the relief provided by the added gage cutter.

The effective depth and cross-sectional area of cut for each cutter are also shown in Figure 13. As radial position increases, both of these quantities decrease due to higher cutter densities and consequently more cutter interaction. Most cutters have effective depths on the order of 0.04 cm (0.16 inch), less than 30% of the feed rate of the bit. Note that the cross-sectional area is proportional to depth of cut for most cutters; but for those near the gage of the bit, the effective depth of cut is relatively large. This is caused by the asymmetrical cutting pattern and the additional rock that gage cutters must remove. A limited number of tests conducted with one side of the cutter against a vertical step in the rock showed that cutter penetrating forces are higher for this configuration, indicating a deeper effective cut as predicted by the modified computer code.

Rock-specific results were computed for the three rock types tested in this study. The relative abrasive wear rate per unit hole length is obtained by dividing Eq. 10 by the same equation solved for the reference cutter 4; thus

$$\text{relative } \frac{dV_w}{dl_h} = \left(\frac{rF/A_w}{rF/A_w} \right)^{n_4} \text{ cutter } i \quad (22)$$

For equal cutter wearflat areas across the bit, it is seen that the relative wear rate for different cutters is independent of the wear model chosen.

The critical penetrating stress σ_c for each cutter is computed according to Eq. 2, using the assumed conditions shown in Table III. The computed penetrating force for each cutter was divided by the wearflat area and the critical penetrating stress to produce stress ratios, σ/σ_c . (Note that this quantity is not normalized with respect to cutter 4.) Since σ_c is a function of cutter speed, it varies with cutter position as well as bit rotary speed. Stress ratios greater than unity imply thermally-accelerated wear.

The results are shown in Figures 14-16. Focusing first on Figure 14 for Berea sandstone, note that the relative abrasive wear rate increases with radial position, despite the reductions seen in relative penetrating force. Apparently, cutter placement under the equal volume criterion does not place enough cutters at large radii to allow penetrating force to be reduced in an inversely proportional fashion, as required by Eq. 11 for equal cutter wear. Gage cutters, in particular, are susceptible to high wear rates due to large radial positions and higher-than-average penetrating forces. The model predicts that gage cutters wear nearly three times faster than the reference cutter near the center of the bit.

Turning to the results for marble and granite in Figures 15 and 16, it is seen that the abrasive wear ratios increase more sharply with radial position as the rock strength increases. This suggests that with bits designed for equal rock removal volume, non-uniformity of wear across the bit face becomes more severe as harder rocks are drilled.

The penetrating stress ratio for Berea sandstone is presented in Figure 14 for a rotary speed of 1000 RPM, corresponding to a penetration rate of 90 m/hr (300 ft/hr). Note that at this high speed, the stress ratio is near unity for all the gage cutters, indicating the onset of thermally-accelerated wear. With only slightly lower speeds, softer rocks, or lower cutter/rock friction coefficients that those considered here, however, all cutters on the bit would operate in the abrasive wear regime, without any thermal effects. These results agree with the generally favorable experience obtained with PDC bit life in soft formations using downhole turbines [28].

With the higher strength rocks, however, thermally-accelerated wear occurs at much lower rotary speeds. In the case of Tennessee marble, Figure 15, penetrating stresses in the gage cutters exceed the critical level at a rotary speed of 100 RPM, corresponding to a penetration rate of only 9 m/hr (30 ft/hr). If the speed is doubled, all cutters greater than 2.5 cm (1.0 inch) from the center of the bit experience thermally-accelerated wear. Frictional temperatures greater than 600°C are computed for the gage cutters at 200 RPM.

In the case of Sierra White granite, the situation is different. The cutter/rock friction coefficient measured for this rock is only 0.07, as opposed to 0.15 for Tennessee marble [16]. Since the critical penetrating stress is inversely proportional to the friction coefficient (Eq. 2), the critical stress is greater for the granite than the marble. As a result, in granite the gage cutters do not approach 350°C until rotary speeds near 200 RPM are used, even though this rock is harder than the marble. Rotary speeds of 400 RPM are required to cause most of the cutters on the bit to wear at an accelerated rate in granite. Of course, at low rotary speeds where thermal effects are not important for either rock, the more abrasive granite will undoubtedly wear cutters at a higher rate than the marble due to its high quartz content.

Again it is seen that cutters 32 and 36 have subnormal values of all measures of wear, due to the relief provided by the added gage cutter. This illustrates the fact that increased cutter density can be used to reduce cutter wear, and redistribution of cutters can be used to modify wear uniformity over the face of the bit. The penalty for increased cutter density is increased bit cost and higher weight-on-bit requirements.

In general, it is concluded that with a bit optimized for equal rock volume, cutters must be moved from the center of the bit toward the periphery in order to equalize abrasive wear. On the other hand, with the exception of the gage cutters, the critical penetrating stress ratio is remarkably uniform over the bit face under the equal rock volume criterion. This suggests that the onset of thermally-accelerated wear is very sudden over the majority of the bit face once a critical rotary speed is attained. To increase the resistance of gage cutters to both abrasive and thermally-accelerated

wear, greater redundancy than that considered here is indicated.

Finally, the total weight-on-bit for each rock was determined by summing individual cutter penetrating forces. The results are shown in Figure 17 for a rotary speed of 100 RPM. These computed results, based upon experimental data for single cutters, seem quite reasonable and again illustrate the sensitivity of penetration rate to weight-on-bit. Correlations of the form

$$R = C_7 W^{n_7} N^{n_8} \quad (23)$$

were obtained for each rock, and the values of C_7 , n_7 , and n_8 are listed in Table IV, together with values obtained using full-scale PDC bit test results. For the full-scale bit tests, where rotary speed and bit weight were considered variables, it was found that a rotary speed exponent of 0.88 is more accurate than the value of 1.0 obtained with the model. The small difference is due to the fact that the models developed in this study do not account for the effects of cutting speed or bit hydraulics (other than cutter cooling) on penetrating forces. The bit weight exponents predicted by the model are also representative of those obtained in the full-scale tests. These encouraging results suggest that the models developed may have use in approximating quantities for parameters needed in PDC bit design.

DISCUSSION

The concepts presented in this paper relative to the rock breakage process are based largely on observations of cutting tests performed at atmospheric pressures. Downhole stresses are known to play a large role in rock breakage mechanisms associated with both roller cone and PDC bits in at least some rock types. In the case of penetration by a roller cone tooth, the primary effect of confining and hydrostatic pressures has been shown to be an increase in friction between crushed rock particles. This increased friction tends to hold particles together in the crushed zone, causing rock failure to appear to be plastic. Maurer [30] termed this pseudo-plastic behavior.

In the case of PDC cutters, very little basic research on the rock failure process under elevated pressures has been reported [26,31,32]. With shale samples, however, it has been shown that increased pressures also cause the drag cutting process to appear more plastic. Furthermore, the compressive strength of most rocks increases under elevated confining pressures. Berea sandstone, for example, has a strength of 130 MPa (18.8 kpsi) under a confining pressure of 13.8 MPa (2.0 kpsi), which is more than twice that measured at atmospheric pressures [33]. Whether or not harder rocks exhibit the same plastic cutting behavior under elevated pressures is not determined in the open literature. It is known, however, that the compressive strengths of some hard rocks do not increase with confining and hydrostatic pressures to nearly the same degree as they do with weaker rocks [34].

The effect of curvature on cutter interaction was neglected in this study. Given the fact that adjacent cutters apparently do not affect cutter forces unless they influence the cross-sectional area

of cut, it seems reasonable to assume that curvature effects due to bit rotation are not significant, at least for large radial locations. Effects due to bit profile curvature were neglected for simplicity. The modified computer code used in this study is, however, capable of taking such profiles into account.

Another cautionary note with respect to the observations reported in this paper is the fact that a very slow cutting speed was used in these tests. Although previous work has shown some effects of speed on single-cutter penetrating forces, the full-scale bit correlations mentioned above indicate that bit feed rate, R/N , does not greatly depend upon rotary speed. As a result, it is reasonable to assume that the speed distribution across the bit radius also has little relative effect among the cutters in this regard.

More accurate correlations for use in bit design could undoubtedly be obtained if downhole conditions were more accurately simulated in single cutter tests. A program is currently underway to measure cutter forces under simulated downhole pressures and at more realistic cutting speeds.

CONCLUSIONS

The following conclusions and observations can be drawn from the findings presented in this paper:

- 1) An abrasive wear model based upon existing data is developed and applied to PDC cutters in rotary drilling. It is shown that thermally-accelerated wear can reduce bit life by two orders of magnitude. Even under conditions where thermal effects are not important, it is found that a cutter develops a significant wearflat by the time 50% of its useful life has been expended. As a result, PDC bits should be designed to operate effectively in a worn condition.
 - 2) To maximize life, a bit should be operated under conditions such that thermally-accelerated wear does not occur and the ratio of penetration rate to rotary speed is maximized. When combined with measured PDC cutting characteristics, this result suggests that a low rotary speed and a high bit weight are conducive to long bit life, provided the bit weight does not exceed the critical level at which thermal wear effects become important.
 - 3) A cutter placement criterion for full-scale bits is developed, based upon the concept of equal cutter wear across the bit face. An expression is derived for determining the design penetrating force for each cutter according to this criterion. This force is shown to be inversely proportional to the cutter's radial position on the bit. It is further found that a bit designed according to the equal wear criterion will also satisfy approximately a criterion based upon equal cutting power per cutter.
 - 4) Cutting experiments in which interaction with adjacent cuts does not occur have shown that the penetrating force required to cut to a given depth is related to the compressive rock strength and the cutter wearflat area. Significant penetration, particularly in hard rocks, does not occur unless the penetrating stress exceeds the compressive strength.
- Two forms of correlations are examined for relating the depth of cut to penetrating stress.
- 5) Cutting experiments also show that interaction between cutters on a bit can significantly reduce cutter forces from those that would develop without interaction. Because of interaction, the depth of cut varies over its width for each cutter. It is shown that the mean value of the depth is a good measure of an effective depth of cut that allows the no-interaction correlations to be used to predict forces on cutters mounted on a bit.
 - 6) An existing computer code for calculating cutter rock removal volumes and optimizing cutter placement for equal volumes was modified to account for cutter wear and to calculate the effective depth of cut for each cutter on a bit face. This code is used to determine in three rock types the penetrating forces and wear characteristics for a hypothetical bit designed according to the equal rock removal criterion. It is shown that the effective depth of cut for each cutter on a bit is only a fraction of the total feed rate of the bit due to cutter interaction.
 - 7) In general, it is found that in the absence of thermal effects, cutters at large radial positions on the bit wear up to three times faster than those near the center of the hypothetical bit considered. This is due to the fact that cutter density according to the equal volume criterion is such that penetrating forces do not vary inversely with radial position as required by the equal wear criterion. Non-uniformity of wear across the bit face was found to increase with rock strength.
 - 8) The effects of rotary speed on the thermal wear potential of the hypothetical bit were assessed for three rock types. In the case of soft rocks, it is demonstrated that thermal effects may not become important until speeds typical of downhole turbines are exceeded. With harder rocks, the critical speed is significantly reduced and is a strong function of the friction coefficient between the cutter and the rock. It is concluded that with a bit designed for equal rock volume removal, the onset of thermally-accelerated wear is very sudden across the bit face once a critical speed is attained.
 - 9) Cutter penetrating forces on a bit face can be significantly reduced by increasing local cutter placement density. In concept, this principle can be used to design a bit for more uniform wear. Such a design would have higher cutter densities at large radii than that for a design based upon the equal volume criterion. Gage cutters in particular suffer from excess penetrating forces and greatly benefit from increased cutter redundancy.
 - 10) The penetrating forces on each cutter and the resulting total weight-on-bit predicted by the models presented in this paper appear reasonable and are typical of those measured in full-scale PDC bit tests.

NOMENCLATURE

REFERENCES

A_r	= cross-sectional area of rock cut - cm^2 (in^2)
A_w	= cutter wearflat area - cm^2 (in^2)
C_1	= constant in cutter data correlations - cm (in)
d	= lateral distance to adjacent cut - cm (in)
f	= thermal response function (see Ref. 6) - $^{\circ}\text{C cm}^2/\text{W}$ ($^{\circ}\text{F ft}^2/\text{hr/Btu}$)
F	= cutter penetrating force - N (lb_f)
F_d	= cutter drag force - N (lb_f)
k_{hf}	= rock formation thermal conductivity - $\text{W/cm}^{\circ}\text{C}$ ($\text{Btu/hr/ft}^{\circ}\text{F}$)
K_f	= cutter/rock friction coefficient
L	= cutting length - cm (in)
L_h	= drilled hole length - m (ft)
L	= cutter wearflat length - cm (in)
n_1	= exponent in cutter data correlations
N	= bit rotary speed - rev/min
P	= cutting power - W (hp)
r	= radial location of cutter on bit - cm (in)
r_c	= radius of cutter compact - cm (in)
R	= bit penetration rate - m/hr (ft/hr)
S_c	= rock compressive strength - MPa (psi)
T_w	= mean wearflat temperature of PDC cutter - $^{\circ}\text{C}$ ($^{\circ}\text{F}$)
T_{fl}	= cooling fluid temperature - $^{\circ}\text{C}$ ($^{\circ}\text{F}$)
v	= cutting speed - m/s (ft/s)
V_r	= volume of rock cut - cm^3 (in^3)
V_w	= cutter wear volume - cm^3 (in^3)
w	= width of wearflat at cutting edge - cm (in)
α_f	= rock formation thermal diffusivity - cm^2/s (in^2/s)
β	= cutter rake angle - deg.
δ	= depth-of-cut in rock - cm (in)
δ_e	= effective depth of cut, Eq. 20 - cm (in)
δ_w	= depth of wear into cutter surface - cm (in)
δ_1	= depth of adjacent cut - cm (in)
μ_d	= cutter drag coefficient, F_d/F
σ	= cutter penetrating stress, F/A_w - MPa (psi)
σ_{cr}	= critical penetrating stress - psi (MPa)

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APPENDIX A

The length of cut per revolution of the bit, divided by the length of hole drilled per revolution, is

$$\frac{dl}{dl_h} = \frac{2\pi r / \cos(\tan^{-1} \frac{R/N}{2\pi r})}{(R/N)} \quad (A-1)$$

where the angle defined by the arctangent term is the angle of inclination of the helix traveled by each cutter as the bit rotates and advances. For all practical cases on a PDC bit, $R/N \ll 2\pi r$; therefore, the inclination of the helical path is negligible, and the cosine term is approximately 1.0. Integrating Eq. A-1 for that approximation produces Eq. 5.

The equation relating the wear volume V_w to the wearflat length L is derived from geometrical considerations. The elemental wear volume, as seen in Fig. A-1, is

$$dV_w = A_{cs} dx \cos \beta \quad (A-2)$$

where

$$A_{cs} = r_c^2 \tan^{-1} \left(\frac{w}{2(r_c - \zeta)} \right) - \frac{w}{2}(r_c - \zeta)$$

$$\zeta = x \sin \beta$$

$$\frac{w}{2} = [r_c^2 - (r_c - \zeta)^2]^{1/2}$$

The wear volume is obtained by summing the elemental wear volumes:

$$V_w = \cos \beta \int_0^L A_{cs} dx. \quad (A-3)$$

Equation (A-3) was integrated numerically for a back-rake angle of 20° and a cutter compact radius of 0.66 cm. The results are shown in Figure A-2. A linear plot is obtained in log-log space, giving a simple relation between V_w and L :

$$V_w = 0.11 L^{2.48} \quad (A-4)$$

or

$$L = 2.4 V_w^{0.4} \quad (A-5)$$

APPENDIX B

Rock cutting tests were conducted on a Cincinnati No. 5 milling machine with a triaxial piezoelectric force transducer and cutter mounted on the head and rock samples mounted on the moving table. Linear cuts were made in the rock while measuring penetrating (vertical), drag (parallel to cut), and side (normal to cut) forces on the cutter. Electrical charges from the force transducer were converted to voltages, amplified, and then recorded

by two methods, a strip-chart recorder and a computer fitted with analog/digital converters.

In addition to the three forces, the following information was stored for each run on floppy disk via the computer: rock type, cutter wearflat area, depth of cut, lateral distance to adjacent cuts and their depths, force transducer amplifier settings, and number of data samples per run. During each run, the three force channels were sampled by the computer at a nominal frequency of approximately 75 Hz, although it was found that this varied depending upon the load on the time-shared laboratory computer. This was not considered a problem because no attempt was made to obtain dynamic force data. Rather, it was desired to obtain time-averaged cutter forces, on the assumption that it is the average cutting conditions that determine the time-averaged wear rate of a PDC cutter. The random computer sampling was therefore used to obtain a statistically large sample so that meaningful average forces under nominally steady-state conditions could be determined. For each cut, between 200 and 700 samples were recorded.

As mentioned in the text, three rock types were tested. The samples were available in various sizes, as shown in Table B-1, but all were large enough so that all data for a given rock type could be obtained on a single sample. After testing, the compressive strength of each sample was measured by coring three 2.5 cm diameter by 2.5 cm long samples from each rock and testing for ultimate failure under unconfined conditions using standard techniques. The values obtained, together with values reported in the literature, are shown in Table B-1. One of the measurements in both the granite and marble was well below the other two respective measurements and the values from the literature. These data points were not considered when calculating the mean values.

The experimental procedure for each rock was as follows. The sample was mounted on the table and the top surface machined with a moderately worn cutter to ensure that the rock was flat and level. A layer of rock at least 0.30 cm deep was then removed using 0.1 cm cuts to ensure that any fine-scale damage left in the rock would be representative of that left by the test cuts. Because of small vertical deflections in the cutting system under high penetrating forces, the actual depth of cut was measured when possible. To simulate effective hydraulic cleaning, the rock surface was vacuumed after each cut to remove rock debris.

The cutter wearflat area was measured by recording an impression of the wearflat with a sheet of carbon paper. The paper was placed between the cutter and an aluminum block while a penetrating force on the order of those measured in the tests was applied. The impression was then overlain with a fine grid and square blocks counted to determine the surface area. The wearflat areas used were large enough that this method was considered accurate. The measured wearflat areas are shown in Figure B-1 as a function of the total length of cut in all three rocks. Note that no wear occurred in the marble or sandstone, but some did occur in the granite. It should be emphasized that these were not wear tests; rather, the wearflat areas were measured for the sole purpose of computing penetrating stresses.

It is beyond the scope of this paper to present all the data obtained in this study; however, the results most pertinent to the concepts discussed in this paper are presented and examined in the text.

TABLE I

SINGLE-CUTTER DATA CORRELATION CONSTANTS

ROCK TYPE	S_c (MPa)	A_w (cm ²)	RANGE IN (cm)	C_5 (cm)	n_5	C_6 (cm)	n_6
Berea sandstone	49	0.26	0.025-0.25	0.130	1.5	-	-
Tennessee marble	122	0.19	0.025-0.25	0.030	2.0	0.13	0.98
Sierra White granite	148	0.19-0.26	0.025-0.25	0.033	2.4	0.18	0.95
Morite [18]	300	2.1	0.150-0.45	0.038	2.2	0.18	1.16

TABLE II

ABSOLUTE VALUES OF PREDICTED PARAMETERS
FOR REFERENCE CUTTER #
(Bit Feed Rate = 0.15 cm/rev)

r	2.604 cm	1.025 inches
V_r	1.50 cm ³ /rev	(0.0917 in ³ /rev)
A_r	0.0887 cm ² /rev	(0.01375 in ² /rev)
e	0.100 cm	(0.0394 inch)
Berea sandstone: F	792 N	(178 lb _f)
Tennessee marble: F	4210 N	(947 lb _f)
Sierra White granite: F	4540 N	(1020 lb _f)

TABLE III

ASSUMED CONDITIONS FOR CALCULATION OF
CRITICAL PENETRATING STRESSES
FOR HYPOTHETICAL BIT

Fluid	water or water-based mud
T_{fl}	50°C (122°F)
f	0.33 °C cm ² /W (1.8E-4 °F ft ² hr/Btu)
L	0.38 cm (0.15 inch)
A_w	0.20 cm ² (0.031 in ²)
k_{hf}	0.019 W/cm°C (1.1 Btu/hr ft°C)
r	0.010 cm ² /s (1.6E-3 in ² /s)
K_f	0.15 - Berea sandstone 0.15 - Tennessee marble 0.07 - Sierra White granite

TABLE IV

CORRELATION CONSTANTS FOR EQUATION 23

ROCK TYPE	BIT DIAMETER (cm)	WEAR CONDITION	C_7 $\left(\frac{1}{\text{hr km}^7 \text{RPM}^8} \right)$	n_7	n_8
PREDICTED RESULTS FOR HYPOTHETICAL BIT					
Berea sandstone	22.2	moderately worn	2.50×10^{-4}	1.96	1.00
Tennessee marble	22.2	moderately worn	5.29×10^{-7}	2.51	1.00
Sierra White granite	22.2	moderately worn	5.41×10^{-8}	2.92	1.00
FULL-SCALE PDC BIT TESTS					
Mancos shale [37]	21.6	new	1.18×10^{-4}	1.97	0.88
Crab Orchard sandstone [38]	16.5	new	1.57×10^{-4}	2.29	0.88
Sierra White granite [38]	16.5	moderately worn	6.33×10^{-7}	2.49	1.00

** Rotary speed not a variable in these tests.

TABLE B-1

ROCK SAMPLE DATA

ROCK TYPE	ROCK-CUTTING SAMPLE SIZE (cm)			UNIAXIAL COMP. STRENGTH (MPa)		
	LENGTH	WIDTH	HEIGHT	MEASURED	MEAN	LIT.
Berea sandstone	39.4	10.2	10.2	54, 47, 46	49	46 [35]
Tennessee marble	50.8	25.4	12.7	125, 120, 88*	123	118 [35]
Sierra white granite	57.9	14.0	11.4	156, 141, 94*	148	170 [36]

* Data not used in calculating mean strength values.

Fig. 1 - Side view of 20° back-rake, stud-mounted PDC cutter (see Fig. A-1 for more details).

Fig. 2 - Effect of cutter wear on penetrating force required to cut hard rock with a single PDC cutter.

Fig. 3 - Growth of PDC cutter wearflat on a bit drilling at constant penetration rate, Eq. 9 [$r=10.2$ cm (4.0 inch); $R/N=0.10$ cm/rev (0.040 in/rev)].

Fig. 4 - Typical rock cutting geometry for a moderately worn cutter on a PDC bit face (shaded area is cross-sectional area of cut; dashed lines represent cutter profiles for interacting cuts).

Fig. 5 - Experimental data on cutter performance for tests with no cutter interaction.

Fig. 6 - Experimental data on cutter performance for tests with no cutter interaction.

Fig. 7 - Ratio of drag to penetrating force for cutting tests with no cutter interaction.

Fig. 8 - Schematic of cutting pattern designed to simulate a typical pattern for a cutter mounted on a bit (only one adjacent cutter for asymmetric pattern).

δ_e = mean depth over width of cut

Fig. 15 - Abrasive wear rate and penetrating force relative to data for cutter 4, and critical penetrating stress ratio for each cutter on hypothetical bit.

Fig. 16 - Abrasive wear rate and penetrating force relative to data for cutter 4, and critical penetrating stress ratio for each cutter on hypothetical bit.

Fig. 17 - Predicted relationships between penetration rate and weight-on-bit for hypothetical bit in three rock types.

Fig. A-2 - Plot of Equation A-3.

Fig. A-1 - Schematic of stud-mounted PDC cutter with back-rake.

Fig. B-1 - Measured cutter wearflat areas in linear cutting experiments.

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