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DESIGN CONSIDERATIONS FOR A HARD-ROCK PDC DRILL BIT*

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ABSTRACT

This paper discusses the potential for developing a polycrystalline diamond compact (PDC) drill bit for hard-rock applications such as geothermal drilling. It is concluded that in order to use the inherently efficient drag cutting process in such severe applications, measures must be taken to reduce cutter penetrating forces in order to prevent thermally-accelerated cutter wear and thereby improve bit life. A procedure is developed for determining the conditions under which waterjets can be effectively used for this purpose by directing them at the rock surface ahead of individual cutters. It is concluded that hard rocks with compressive strengths as high as 30 kpsi (200 MPa) may be drillable with a hybrid PDC/waterjet bit using pressures that conventional oil field pumping technology is capable of providing. Extremely hard rocks might be drilled with such a bit using nozzle pressures well below those required to effectively cut the rock with waterjets alone.

INTRODUCTION

Part of the relatively high costs of geothermal drilling, as compared with those for petroleum resources, is due to the generally poor performance of conventional roller cone bits in hot, abrasive environments. Bearing and gage wear, in particular, often combine to reduce bit life to 100 to 200 feet (30-60 m) [1]. Bit and tripping costs are therefore substantial in wells several thousand feet deep.

Under certain conditions, tripping frequency can be greatly reduced by using bits employing polycrystalline diamond compact (PDC) drag cutters. In soft-formation petroleum drilling, bit runs as great as ten times those achievable with roller cone bits are common, with the record footage drilled by a single PDC bit currently standing at over 20,000 feet (6100 m) [2]. PDC bits have not been used routinely in geothermal drilling, but tests in relatively soft formations in the Imperial Valley achieved a doubling of bit life and penetration rate over those obtained with roller bits run in the same hole [3].

In the hard, abrasive formations that are more typical of geothermal drilling, adequate PDC bit life has not been demonstrated. Laboratory and field tests have shown, in fact, that extremely rapid wear of PDC cutters can occur when drilling hard rock [3]. The extreme stresses required to penetrate hard formations produce excessive frictional heating of the cutter, which leads to thermally-accelerated wear. Elevated ambient temperatures reduce the ability of the drilling fluid to cool the cutters, thereby worsening the problem. The drilling environment for the cutter is particularly severe when air is used as the drilling fluid.

Because of the inherently high rock-removal efficiency of drag cutting relative to that of crushing, PDC bits can generally drill most formations at higher penetration rates than roller cone bits. If adequate bit life in hard formations could be achieved, PDC bits could play a major role in reducing geothermal drilling costs. An equally effective improvement would be to maintain adequate penetration rates while greatly improving bit life over that achievable with roller bits in such hostile environments. For several years, studies have been underway at Sandia National Laboratories to develop the basic understanding of design and operating parameters required to determine the potential for using PDC bits in geothermal drilling. The conclusion has been reached that PDC bits have the potential for effectively drilling hard-rock formations only if waterjet assistance is provided for the most highly stressed cutters on the bits. This paper presents the major considerations used in reaching that conclusion and briefly discusses a planned program to develop a hybrid PDC/waterjet bit for deep-hole, hard-rock drilling.

MECHANICS OF DRAG CUTTING

Consider a PDC drag cutter, shown schematically in Figure 1, moving laterally against a rock surface at speed V under an applied penetrating force F. Penetration of the rock occurs when the normal stress between the cutter

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and the rock exceeds some threshold value. The mean penetrating stress is

\[ \sigma = \frac{F}{A_w} \]  

(1)

where \( A_w \) is the cutter wearflat area in contact with the rock. The stress distribution beneath the cutter, however, is not uniform. The presence of the wear-resistant synthetic diamond layer on the face of the cutter prevents rounding of the cutting edge during drilling, a phenomenon that is prevalent with cemented carbide drag cutters used in underground mining machines [4]. The sharp diamond cutting edge concentrates stress in the rock beneath the cutter, with the result that local stresses may be significantly higher than the mean stress.

Failure of hard, brittle rocks under the action of a drag cutter occurs by a process of crushing and fracture initiation and propagation [5]. Crushing occurs primarily along the cutting edge and generates considerable cutting fines. These fines tend to accumulate ahead of and beneath the cutter, acting to distribute the stresses and thereby cushion the rock from the stress concentration provided by the sharp cutting edge. Fractures in the rock initiate near the cutting edge and propagate downward and ahead of the cutter to form a rock chip.

It would be desirable to have available a model for predicting fracture propagation in the rock so that the relationship between cutter forces and penetration rate could be predicted for a given set of conditions. Because of the complexity of fracture propagation in brittle materials and the inhomogeneity of rock, however, it is not likely that a reliable analytical or numerical solution will be forthcoming in the near future. We must therefore resort to experimental data to obtain the required relationships.

Shown in Figure 2 are available single cutter data [1,6,7] relating depth-of-cut to penetrating stress. Useful data for this purpose are scarce, because most investigators have used sharp cutters. Since cutters quickly develop a measurable wearflat before a significant fraction of their useful life is expended, only data obtained with such wearflats are considered relevant. These limited data seem to agree with analytical solutions [8] for the rock stresses beneath a tool, which show that significant rock penetration does not occur until a penetrating stress on the order of the uniaxial compressive rock strength is applied. Each set of data extrapolates to a zero depth-of-cut at a penetrating stress near the uniaxial compressive strength of the respective rock type; thus

\[ \delta = 0 \text{ when } \sigma \leq S_c, \]  

(2)

where \( \delta \) is the depth-of-cut and \( S_c \) is the compressive strength of the rock. At stress levels above \( S_c \), the depth-of-cut increases monotonically, suggesting that the data might be correlated in the form

\[ \delta = C(\sigma/S_c - 1)^m, \]  

(3)

where \( C \) and \( m \) are determined by experiment. These correlation parameters have been determined for the data of Figure 2 and are listed in Table I. The curves of Figure 2 represent the results. As seen in the figure, the form of the correlation seems to provide a sufficiently accurate fit for the present purposes. It is interesting to note that the values of \( C \) and \( m \) listed in the table do not vary by much more than a factor of two among the various data sets, even though the types of cutters and test conditions used were significantly different. If parameters such as rock type, cutter geometry, ambient pressure, cutter speed, hydraulic cleaning, and interaction with rock grooves cut by adjacent cutters can be
simulated in the laboratory, single cutter data useful for bit design can be obtained. More appropriate forms of equation 3 may be used if the effects of some of these parameters can be included in the correlation.

Under elevated lithostatic or hydrostatic pressures, rocks generally become stronger and failure becomes more plastic. A more general interpretation of $S_o$ should therefore be the cutting strength of the rock. This parameter can be determined experimentally for a given set of conditions by increasing the penetrating stress gradually until penetration of the rock surface is achieved. Simultaneous measurements of the drag force will yield friction coefficient data, which is also useful for bit design purposes.

For a given weight-on-bit, the bit as a whole will attain a certain penetration rate $R$. The relationship between the bit penetration rate and the depth-of-cut for a given cutter is

$$\delta = \frac{R}{N n}$$

where $N$ is the bit rotary speed and $n$ is the number of cutters located for redundancy at the same radius on the bit as the cutter under consideration. Substituting equation 3 into the above equation gives the result

$$\sigma = S_c \left( \frac{R}{N n} \right)^{1/m} + 1$$

We now have an equation for determining the penetrating stress required for each cutter in order to attain a desired bit penetration rate.

**THERMAL WEAR EFFECTS**

We have seen that a minimum penetrating stress must be applied to the rock surface before penetration is achieved. There are, however, limitations on the stresses that a PDC cutter can withstand without experiencing accelerated wear. Friction between the cutter and the rock represents a conversion of mechanical energy to heat. An analytical/numerical model has been developed for partitioning this frictional heat between the cutter and the rock and determining the resulting temperature distribution throughout the cutter [9]. It has been found that extremely high cutter temperatures can develop under certain drilling conditions.

A correlation based upon this model and experimental data has been developed between cutter wear rates and the mean temperature across the wearflat [10]. Under conditions that produce wearflat temperatures below approximately 350°C (662°F), volumetric wear rates are relatively low and constant with temperature. At higher temperatures, wear accelerates and can quickly destroy a PDC cutter. Based on this observation, an equation was developed for determining the critical mean wearflat temperature $T_c$, above which thermally-accelerated wear occurs for a given cutter [3]:

$$\sigma_{cr} = \frac{(350^\circ C - T_c)}{2\pi N n f} \left( \frac{1 + 3}{4} \pi^2 \left( \frac{2Rn}{X^2L} \right)^b \right)$$

To further identify the causes of thermally-accelerated wear, stresses throughout a PDC cutter were computed [11] using a finite element structural computer code. Computed temperature distributions, together with appropriate mechanical loads, were used as boundary conditions for the structural model.

In general, it was found that thermal stresses in the cutter become severe under conditions that produce mean wearflat temperatures greater than 350°C. Large thermal gradients and a thermal expansion coefficient mismatch at the diamond-tungsten carbide interface combine to produce significant compressive and tensile stresses in various parts of the cutter. Under certain conditions, compressive stresses in the wearflat region are sufficient to cause plastic deformation in the tungsten carbide, which produces voids in the microstructure that serve as crack nucleation sites. The normal abrasion process also produces microcracks in hard, brittle materials such as these.

Once initiated, microcracks are easily propagated, particularly in the presence of tensile stresses. Crack propagation eventually leads to the development of wear particles. It was found that tensile stresses in the wearflat region develop under normal air drilling conditions. When using water or mud as the drilling fluid, tensile stresses can develop along the wearflat if the bit weight is suddenly removed or if bit bounce occurs, causing rapid cooling and thermal shock of the wearflat.

Under conditions producing wearflat temperatures below 350°C, it was found that both compressive and tensile stresses are greatly reduced. This suggests that the thermally-accelerated wear that occurs above this critical temperature is somewhat inherent to the materials used in PDC cutters. Although some optimization of the microstructural design to improve wear resistance may be possible, significant improvements in materials technology may not be forthcoming in the near future. For the present, the maximum wearflat temperature of 350°C should therefore be accepted as a limitation on the design and operation of PDC bits.

**IMPLICATIONS FOR BIT DESIGN AND OPERATION**

The range of adequate but permissible penetrating stresses for PDC drag cutting has been shown to be bounded by a minimum required to cut rock and a maximum above which thermally-accelerated wear occurs. This provides guidelines for bit design and operation and defines the maximum strength rock that can be drilled in a given application.
The critical penetrating stress is plotted in Figure 3 for the typical hard-rock drilling conditions listed in Table II. Also shown are unconfined compressive strengths for several geothermal rock types. Note that the critical penetrating stress decreases rapidly with bit rotary speed. At speeds above about 250 RPM, hard rock (S > 20 kpsi) cannot be penetrated without thermally-accelerated cutter wear. Even at low rotary speeds, significant penetration rates cannot be achieved in very hard rock since the required penetrating stress would exceed the critical level.

To improve the ability of PDC cutters to effectively cut hard rock, measures must be taken to increase the critical penetrating stress or reduce the stress levels required to cut the rock. A technique discovered by Hood [6] for underground mining applications has the potential for accomplishing both. The concept consists of directing a waterjet at the rock surface immediately ahead of the cutter. Such a jet is effective in improving cutter cooling in the wear flat region and may reduce friction with the rock surface. Both of these should result in a larger critical penetrating stress. Jets are also effective in removing crushed rock particles from the cutting edge region, thereby improving the concentration of stress in the rock along the sharp diamond edge. If the waterjet contains sufficient energy, fractures created by the drag cutter in the rock can be hydraulically extended by the fluid pressure, thereby further reducing the mechanical forces required to achieve a given depth-of-cut.

Some of the data obtained by Hood [6] in extremely hard rock are shown in Figure 4. These results were obtained with two 7500 psi (50 MPA) waterjets directed 0.08 inch (2 mm) ahead of the (non-PDC) drag cutter. Note that a significantly greater depth-of-cut can be achieved with a given penetrating force if jet assistance is provided. Alternatively, the force required to achieve a given depth-of-cut is significantly reduced with jet assistance. Similar data obtained with nozzle pressure drops as low as 1500 psi (10 MPA) showed that the effect is still surprisingly strong at low pressures.

Data obtained by Dubignon [12] for a softer but still very hard rock are presented in Figure 5. Here the ratios of the measured cutter forces with jet assistance to those measured without assistance are plotted as a function of nozzle pressure drop. Data are shown for both the penetrating and drag forces. Note that jet pressures of 2500 psi (17 MPA) are sufficient to reduce penetrating force (and stress) by 50%. An

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**Fig. 3** - Critical penetrating stress for thermally-accelerated wear, computed for conditions listed in Table II.

**Fig. 4** - Effects of waterjet assistance on drag cutter penetrating forces with 7500 psi nozzle pressure drop (after Reference 6).

**Fig. 5** - Effects of waterjet nozzle pressure drop on drag cutter forces for 0.24 inch depth-of-cut (after Reference 12).
impressive 75% reduction is possible with nozzle pressures of 9000 psi (62 MPa). The significant reductions in drag force suggest that torque requirements for a PDC bit using jet assistance could be reduced from the relatively high values experienced with conventional PDC bits.

The question now at hand is whether or not such reductions in cutter forces are sufficient to allow significant penetration rates to be achieved in hard rock without causing thermally-accelerated wear. It is clear that much more data and analysis are necessary before this question can be answered definitively; however, a prediction based upon equations 5 and 6 can be made. For a given penetration rate, the percentage reduction in penetrating stress required to prevent thermally-accelerated wear of a given cutter is

\[ A\% = \left(1 - \frac{\sigma}{\sigma_{cr}}\right) \times 100 \quad (7) \]

Because of the proportionality between stress and force for a given wearflat area, \( A\% \) is also the percentage reduction in penetrating force required to prevent thermally-accelerated wear. An example will serve to illustrate the use of this equation.

For simplicity, we assume that the most severely stressed cutter on a 12-1/4 inch (31.1 cm) bit is located at a radius of 6 inches (15.2 cm) and does not have a pick-up cutter for redundancy, i.e. n = 1. In designing a bit, we would try to simulate the conditions such a cutter would experience downhole and conduct single cutter tests to obtain a correlation between penetrating stress and depth-of-cut in the range of interest. In this example, we assume that we have obtained the correlation given for Westerly gray granite in Table 1. The unconfined compressive strength for this hard rock is reported to be 33.8 kpsi [13]. Values for the other variables represented in equation 7 are listed in Table 2 and are based upon estimates for typical geothermal drilling conditions.

The results are shown in Figure 6. The percentage reduction in penetrating force required to prevent thermally-accelerated wear is plotted against bit rotary speed for a variety of penetration rates. Note that only the curves for relatively low penetration rates intersect the x-axis, meaning that higher rates cannot be achieved without taking measures to reduce cutter forces.

At low rotary speeds, penetration rates of 10 to 20 ft/hr (3-6 m/hr) can be sustained without accelerated wear if penetrating forces can be reduced by 50%. Such reductions were obtained by Dubugnon with a similar rock using jet pressures of only 2500 psi (17 MPa). At bit rotary speeds near 600 RPM (not shown), the curves converge to a single curve at a required force reduction of approximately 70%, increasing to nearly 80% at 1000 RPM. Thus the required penetrating force reductions at high rotary speeds are achievable only with much higher jet pressures. It is clear that rotary speeds typical of conventional rotary drilling (200 RPM) are preferable over downhole motor speeds in hard-rock applications.

The results of the analyses presented above suggest that significant improvements in the ability of PDC bits to drill long intervals in hard rock without causing thermally-accelerated wear are possible. The question now at hand is whether or not such improvements are sufficient to allow significant penetration rates to be achieved in deep, hard-rock formations that currently experience with conventional PDC bits, such as those used in geothermal drilling. Tests under atmospheric and elevated ambient pressures are planned to provide data for this purpose. An approach based upon the concepts reviewed in this paper is being developed for designing a bit for uniform cutter wear across the bit face. Such a design would maximize overall bit life and optimize the use of costly cutter materials.

**CONCLUSIONS**

The following summary contains the major considerations discussed in this paper:

1) A threshold penetrating stress exists which must be exceeded before a significant depth-of-cut is achieved with a drag cutter on a hard-rock surface. This threshold stress correlates well with the uniaxial compressive strength for cutting tests conducted under unconfined conditions.

2) A critical penetrating stress between a PDC cutter and a rock surface exists, above which thermally-accelerated cutter wear occurs. Such wear characteristics are inherent to the materials
used to construct a PDC cutter and impose limitations on the design and operations of PDC bits.

3) In hard-rock applications, the critical penetrating stress is less than or only slightly greater than the threshold penetrating stress. As a result, only relatively low penetration rates can be sustained in hard rock without causing accelerated cutter wear and reduced bit life.

4) Waterjets directed at the rock surface ahead of a cutter can significantly reduce the penetrating stress required to achieve a given depth-of-cut in hard rock. A procedure is developed for determining the conditions under which waterjet assistance would increase the penetration rates that could be sustained without causing thermally-accelerated cutter wear.

5) A program is underway to determine the feasibility of developing a workable PDC/waterjet bit for use in geothermal drilling. Preliminary analysis indicates that most hard geothermal formations may be drillable with such a hybrid bit using nozzle pressure drops of 3 to 4 kpsi (21-28 MPa). Effectively drilling the hardest formations, such as andesite and quartzite, will probably require nozzle pressures on the order of 7 to 10 kpsi (48-69 MPa) if thermally-accelerated cutter wear is to be prevented.

NOMENCLATURE

- \( A_w \) = cutter wearflat area - \( \text{in}^2 \) (cm\(^2\))
- \( C^* \) = correlation constant in equation 3-in.(cm)
- \( \rho_c \) = thermal response function (see Refs. 9-11)
- \( r \) = radial location of cutter on bit - \( \text{in} \) (cm)
- \( n \) = correlation exponent in equation 3
- \( m \) = number of cutters at given radius on bit
- \( N \) = bit rotary speed - rev/min
- \( PDM \) = positive displacement motor
- \( r \) = radial location of cutter on bit - \( \text{in} \) (cm)
- \( R \) = bit penetration rate - \( \text{ft/hr} \) (m/hr)
- \( S_c \) = rock compressive or cutting strength - \( \text{psi} \) (MPa)
- \( T_F \) = cooling fluid temperature - \( \degree F \) (\( \degree C \))
- \( V \) = cutter translation speed - \( \text{ft/s} \) (m/s)
- \( \delta \) = depth-of-cut in rock - \( \text{in} \) (cm)
- \( \Delta \) = percentage reduction in penetrating force (or stress) required to prevent thermally-accelerated cutter wear
- \( \mu \) = cutter/rock friction coefficient
- \( \sigma \) = mean penetrating stress - \( \text{psi} \) (MPa)
- \( \sigma_{cr} \) = critical penetrating stress - \( \text{psi} \) (MPa)
- \( \chi_2 \) = rock thermal diffusivity - \( \text{in}^2/\text{s} \) (cm\(^2\)/s)

REFERENCES


