



Model of the Impregnated Diamond Bits

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Abstract

Paper presents a very first attempt of development of the analytical relationships between the impregnated bit penetration rate and the matrix and diamonds wear rates, and rock drillability and abrasiveness. Model allows calculating the number of diamonds exposed at the face of the bit and the number of equivalent blades, as well as a rate of penetration as a function of diamonds size and their content in the bit matrix. To simplify the presentation of the model, it is assumed that the spherically shaped diamonds destroys rock and the rock behavior during cutting may be approximated by that of a rigid-plastic Coulomb material.

These relationships would allow determination of the optimum diamonds size distribution, the rates of matrix and diamonds wear processes that assure an uniform matrix wear and a maximum working time of the diamonds at the bit face before they come out from the matrix body.

Introduction

Drill bit technology continues to advances in spite of the fact that bits usually constitute a small fraction of a well's overall cost. However, the drilling system performance influences a large proportion of the overall cost and a bit related problem that prevents the drilling system from achieving its objectives can be very expensive. For that reason, developments in bit technology feature continue to be important. Recent overview of bit technology indicates that new applications require improving bit's performance, steerability, ability to control vibrations, or ability to drill a uniform-quality wellbore that is more important than further increases in bit penetration rate or material durability.

Recent application of new impregnated diamond bit technology proved these bits capabilities to drill deep

intervals where increasing on-bottom drilling time and reducing costly trips for a new roller cone bits balances the economics and reduces drilling risks. A new interrupted impregnated cutting structure improved rate of penetration and bit life drilling hard and abrasive sandstone but with the added capability of drilling faster in the softer shale and non-abrasive rock. This technology combined with changes in drilling practices has increased the overall average penetration rate, kept the bit drilling on bottom, and replacing multiple bits. The longer bit runs also reduced the number of bit trips limiting potential problems associated with tripping operations through depleted and sensitive formations¹.

A new innovative cutting structure offers unique advantages drilling hard/abrasive intervals more economically and avoids the clogging tendencies of the earlier bits, as well as drill more efficiently². Impregnated bits have hard, synthetic diamonds impregnated in a matrix of hard tungsten carbide particles with a softer binder. The cutting structure abrades by abrasive drilling action, which exposes new diamonds in what is referred to as self-sharpening wear. The rate of the abrasion should occur fast enough to expose new diamonds before the existing diamonds develop large wear flats and slows the rate of penetration. Conversely, the abrasion rate should be slow enough so that the bit does not wear out prematurely. For this reason, matrix selection is critical for matching the impregnated bit to the application. As reported by West et al.¹, based on the extensive laboratory and field testing, three different types of newly developed matrix material allowed design engineers to adjust the abrasion resistance to the interbedded lithology.

In this paper an impregnated bit performance model is presented that allows analytical investigation of the relationships between the bit rate of penetration, the rates of diamonds and matrix wear, respectively, and the bit and rock properties/characteristics. Model consists of three basic equations for the rate of penetration, rate of

diamonds wear, and rate of matrix wear as a function of diamonds size, bit carats, bit profile and the parameters which characterize rock drillability, and the diamonds and matrix resistance for abrasive wear during drilling. Model is developed based on the concept of the equivalent diamond blades, presented by Peterson³, diamond wear model, presented by Ziaja and Miska⁴, and previously developed theory of rock destruction by diamond cutters presented by Rowley and Apple⁵. Thus, it is assumed that, with a perfect cleaning, rock behavior during cutting may be approximated by that of a rigid-plastic, Coulomb material. This theory, as proved by the experimental results⁶, allows determining the axial and tangential forces necessary for drilling in a given lithology. In this paper, the equations of the rate of penetration, and the diamonds and matrix rate of wear, respectively, are developed based on the concept of the specific energy necessary for the unit rock destruction, diamonds and matrix wear, respectively.

Theory of Impregnated Bit Performance

A complete analysis of impregnated diamond bit performance should take into account the interaction of the drilling fluid with the mechanics of the rock destruction. All material loosened by the diamonds must be carried away by the drilling fluid as it flows between the matrix on the cutting face of the bit and the rock being cut. The geometry of the clearance between the bit/matrix and rock is dependent on the diamond exposure and the diamond cutting action. A complete analysis of bit performance including bit hydraulics effects has not been attempted. The present study relates primarily to mechanics of cutting and bit wear. The performance of an impregnated bit is determined for conditions of "perfect cleaning". Using the previous theory of cutting action, the depth of cut of the diamonds is determined in terms of bit geometry, diamonds amount and their size, and drilling rate.

Most impregnated bits have a relatively large number of diamonds spaced randomly but rather closely together. Irregularities in diamond shape and variation due to manufacturing procedures result in deviations that are as large or larger than the average depth of cut of the individual diamonds. On the bit cutting structure, there are some diamonds that do not cut as they are slightly exposed, some already worn but still in matrix, only some cutting at the maximum depth. Statistical treatment of the diamonds shape and the depth of cut are assumed to be the most practical. Thus, it is assumed that, on average, optimum depth of cut is equal to a half of their exposure (1/6 of diamond diameter) but the diamonds fall out from the matrix when their exposure due to matrix wear is equal to a half of their diameter (see Figure 1).

Rate of Penetration Equation

Assuming the diamonds are uniformly spaced in the matrix, the diamonds at any given radius (r_d) share the work equally. For model presentation simplicity, it is assumed that the drilling conditions and the rock formation remain constant and that steady-state conditions prevail.

Consider the volume of matrix, V_{mb} , containing a given number of carats, D . Thus, the number of diamonds exposed at the bit cutting surface, F_b , is:

$$n_d = F_b \left(\sqrt[3]{\frac{D}{V_{mb}}} \right)^2 \dots\dots\dots(1)$$

Consider the cutting action of a diamonds of an annular element of the bit's cutting surface, of radius r_d , as shown in Figure 2. A geometrical expression is obtained for the volume of rock that must be removed by a statistical diamond at this radius:

$$V_r = h_e n_e (2\pi N r_d) t = 0.1018 (\pi N r_d) d^2 t \dots\dots\dots(2)$$

Assuming the cutting forces F_a and F_t as defined by Rowley and Appl⁵ and the concept of specific energy required for destruction of a unit volume of rock, S_r , the energy required for destruction of a given rock volume is:

$$E_r = 2\pi N r_d F_t t + F_a \frac{dh}{dt} t = S_r V_r \dots\dots\dots(3)$$

Substituting equation (2) for the volume of rock destructed, V_r , into equation (3) and solving for dh/dt yields an equation for the bit's rate of penetration:

$$\frac{dh}{dt} = 2\pi N r_d n_{dr} \left[\frac{0.05093 d^2 S_r}{F_a} - \frac{F_t}{F_a} \right] \dots\dots\dots(4)$$

Equation (4) is a function of the diamonds size and their density (carats) in the matrix of a bit but.

Diamond Wear Rate Equation

Assuming the same concept of a specific energy, S_d , the energy required for an abrasive wear of a given diamond may be determined by the following equation:

$$E_d = 2\pi N r_d t \mu_d F_a = 6 S_d V_d \frac{\Delta m}{d} \dots\dots\dots(5)$$

Substituting for volume of worn diamond, V_d , from a diamond geometry yields,

$$\frac{dx}{dt} = \frac{N r_d \mu_d d F_a}{3 S_d \Delta m (dx - x^2)} \dots\dots\dots(6)$$

Above equations allows analyzing the relationship between the matrix and diamonds wear rate, respectively.

Matrix Wear Rate Equation

It is assumed that bit matrix is worn due to the abrasion resulting from the cuttings and fluid flow between the rock and matrix body. This process resulting in the bit support against the weight on bit causes the weight on diamonds to be less than that calculated from the weight on bit. This opposite force called "pump-off force" is assumed to cause an abrasive wear of the matrix, which is determined by the following equation:

$$\frac{dm}{dt} = \frac{2\pi N r_d (WOB_j - F_a)}{S_m \left(\sqrt[3]{\frac{D}{V_m}} \right)^{-2} \left[1 - \frac{D \pi d^3}{V_m 6} \right]} \dots\dots\dots(7)$$

Equating equation (6) and equation (7) allows analyzing the conditions for which linear wear of the matrix and diamonds assures the optimum matrix matching for the drilled lithologies.

Bit Performance Modeling

Above equations have been developed assuming the unit weight per working diamond is equal to the sum of axial cutting force and so-called "pump off" force, F_m , causing matrix wear.

$$WOB_j = F_a + F_m \dots\dots\dots(8)$$

Also, it is assumed that unit tangential force F_{tqj} at each working diamond, resulting from an applied bit torque, is in equilibrium with the tangential forces acting on the diamonds during drilling:

$$F_{tqj} = F_t + \mu_d F_a + \mu_m F_m \dots\dots\dots(9)$$

All of the developed equations relate to the diamonds performance at the given bit radius, r_d . In determining the characteristics of any given bit, it is desirable to make calculations for each ring of the bit cutting structure and a given rate of bit penetration. Since the calculations become complex, a computer program makes it possible to determine bit performance for a given bit, specified in terms of geometry, by simply inserting parameters for rock properties and drilling conditions. Empirical parameters defined in the model as rock drillability, diamond and matrix abrasive resistance and the coefficients of friction may be estimated from the offset wells/previous bit run data. Solving five (5) equations of the model for the unknowns mentioned above yields:

$$S_r = \left(\frac{H}{2\pi N r_d T_b} + \frac{F_t}{F_a} \right) \frac{F_a}{0.05093 d^2} \dots\dots\dots(10)$$

$$S_d = \frac{\Delta m A_1 (F_{tqj} - F_t) - A_2 (WOB_j - F_a) (E_d - S_r V_r T_b)}{F_a \Delta m A_1 + \Delta m A_2 (WOB_j - F_a)} \dots\dots\dots(11)$$

$$\mu_d = \frac{S_d \Delta m d^2}{27 N r_d F_a T_b} \dots\dots\dots(12)$$

$$S_m = \frac{E_d - \Delta m S_d - S_r C_1 T_b}{\Delta m} \dots (13)$$

$$\mu_m = \frac{S_m}{A_1} \dots (14)$$

Equations for A_1 , A_2 , are as follows:

$$A_1 = \frac{2\pi N r_d (WOB_j - F_a) T_b}{\Delta m \left(\sqrt[3]{\frac{D}{V_{mb}}} \right)^{-2} \left[1 - \frac{D}{V_{mb}} \frac{\pi d^3}{6} \right]} \dots (15)$$

$$A_2 = \frac{27 N r_d F_a T_b}{\Delta m d^2} \dots (16)$$

According to the above theoretical assumptions and the developed equations, it is possible to analyze the affect the bit design has on the bit performance at each radius/segment of the bit. Figure 3 and Figure 4 show, for example, the distribution of the diamonds wear and weight on diamonds, respectively, as a function of an arbitrary bit profile (see Figure 5) and diamonds sizes (60 stones per carat).

Conclusions

1. Presented model attempts for the quantification of the impregnated bit design features in matrix selection based on the relationship between matrix abrasion resistance, diamond wear rate and rock abrasivity/drillability.
2. Diamond density and stone size expressed in terms of equivalent blades allows diamond density modifications appropriate for a given bit profile and rock properties, so that the optimum diamonds and matrix wear may be predicted and/or modified based on the field data.
3. More field and/or lab data are required to verify the validity of the presented theoretical model of the impregnated diamond bits.

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Nomenclature

- a = diamond width of cut, in
 $a_e = 0.6035 a$ = equivalent width of cut, in
 d = diameter of diamonds, in
 D = amount of carats in bit, carats
 E_d = energy used for diamond wear, ft-lbf
 E_m = energy used for matrix wear, ft-lbf
 E_r = energy used for rock destruction, ft-lbf
 F_a = axial cutting force, lbf
 F_b = bit face surface (cutting structure only), in²
 F_m = axial force acting on matrix, lbf
 F_t = tangential cutting force, lbf
 F_{tqj} = tangential force at diamond, lbf
 h = diamond depth of cut, in
 $h_e = 0.6794h$ = equivalent depth of cut, in
 H = bit footage, ft
 m = linear wear of the matrix, in
 n_d = number of diamonds on the bit cutting structure
 n_{dr} = number of diamonds at the radius r_d
 N = bit rotational speed, rpm
 ROP = drilling rate of penetration
 r_d = radius of diamond location, in
 rpm = revolutions per minute
 S = diamonds grit, carats/stone
 S_d = diamond specific energy, hp/in³
 S_m = rock specific energy, hp/in³
 S_r = matrix specific energy, hp/in³
 t = time, hr
 T_b = bit drilling time
 T_d = diamond drilling time, hr
 TQ = bit torque, ft-lbf
 TQ_j = diamond torque, ft-lbf
 V_d = worn volume of diamond, in³
 V_m = bulk volume of matrix, in³
 V_{mb} = worn volume of matrix per diamond, in³
 V_r = volume of rock destroyed by diamond, in³
 WOB = weight on bit, lbf
 WOB_j = weight on diamond, lbf
 x = linear wear of the diamond, in
 μ_d = coefficient of friction between the rock and diamond
 μ_m = coefficient of friction between matrix and flowing fluid with cuttings

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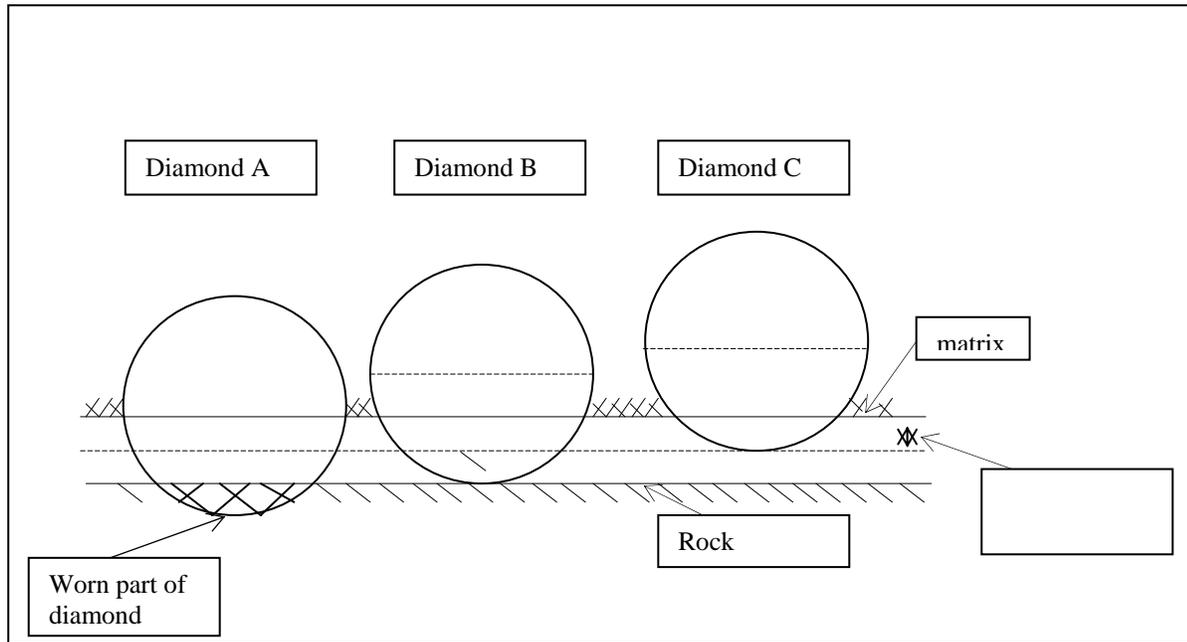


Fig. 1- Concept of impregnated bit performance.

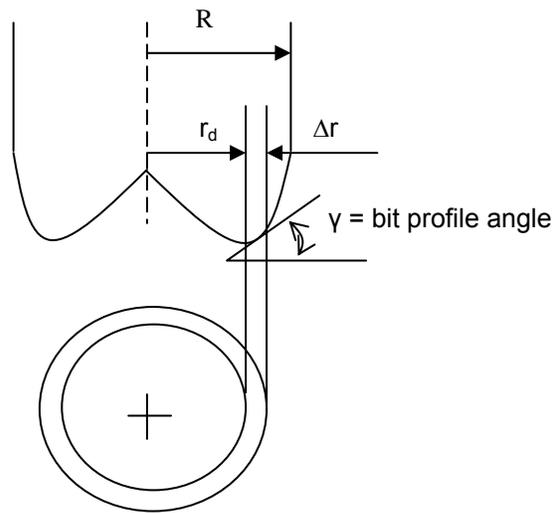


Fig. 2- Annular element of bit cutting structure.

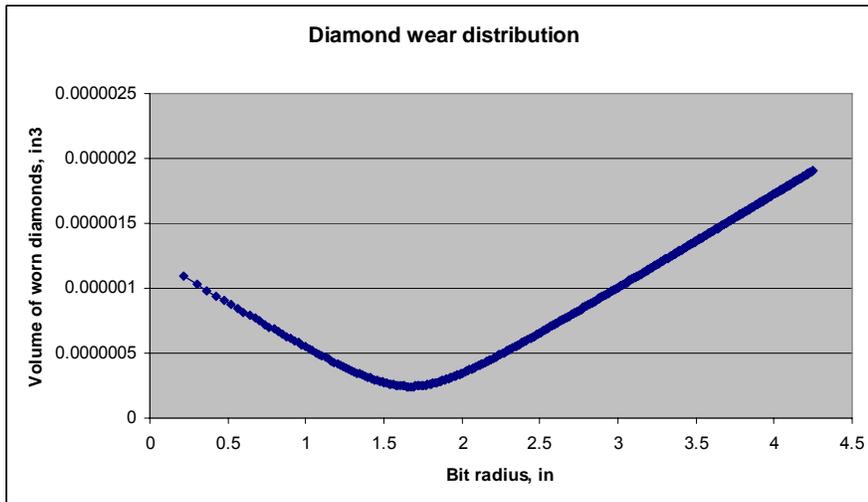


Fig. 3 – Distribution of the diamond wear.

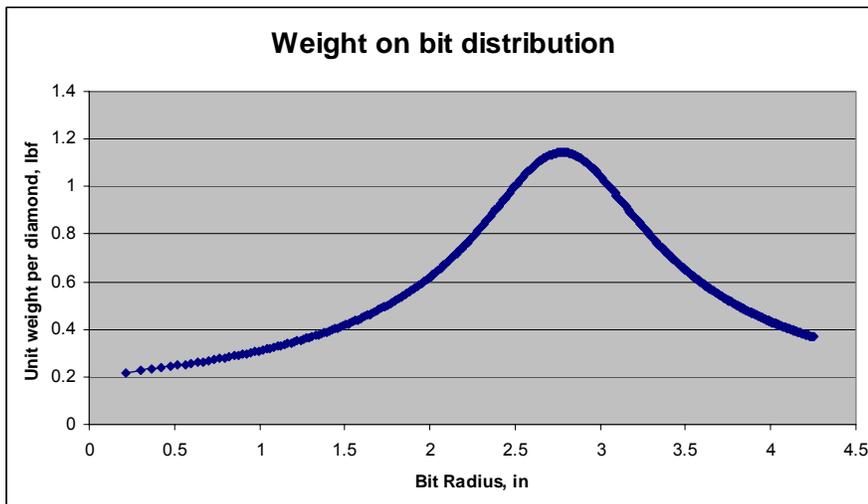


Fig. 4 – Weight on bit distribution.

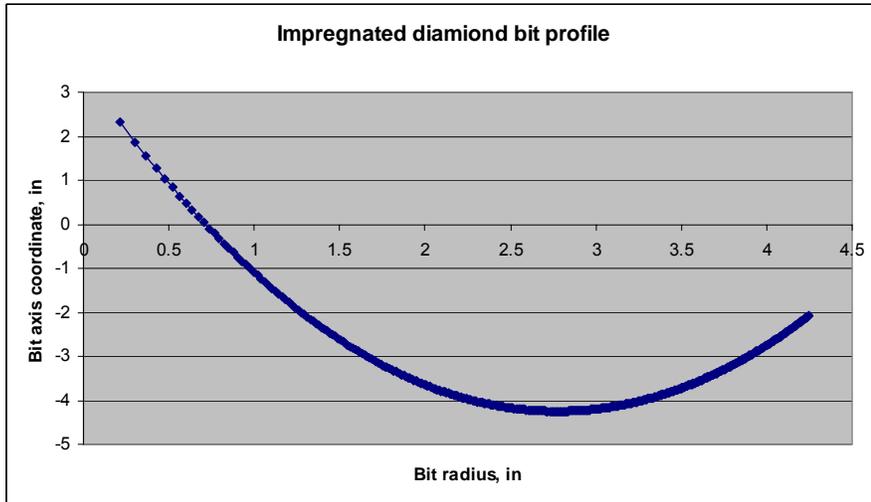


Fig. 5 – Impregnated diamond bit profile.

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