OPTIMAL DESIGN OF CORING BIT CUTTING EDGE IN PERCUSSIVE/VIBRATORY DRILLING

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ABSTRACT

The objective of this study is to develop an analytical method for the optimization of the design of coring bits of vibratory drills with cutting teeth that percussively penetrate brittle material. This optimization is intended to improve the drill rate of Ultrasonic Driller and Corer (USDC) that was developed by scientists from JPL and engineers from Cybersonics, Inc. The USDC was developed for possible in-situ sample and other extraterrestrial applications in future NASA missions. A theoretical and experimental investigation was undertaken to study the rock-bit penetration characteristics and derive the analytical formulation of the specific energy for coring bit with wedge-shape cutting teeth, based on rock fracture mechanics. The numerical analysis was performed based on two analytical models. There exists an optimal spacing/depth ratio of cutting teeth, and the optimal numbers of cutting teeth on bottom annulus of coring bit can be designed to achieve a minimum total specific energy for the coring bit. The results of the preliminary laboratory drilling tests follow the trend predicted by theoretical analysis.

1 INTRODUCTION

In the present work an optimal design method based on rock fracture mechanics is developed for the coring bit with a series of cutting teeth located along the bottom annulus penetrating brittle materials during percussive and vibratory drilling. The specific problem addresses the need to improve the drill rate of an Ultrasonic Driller and Corer (USDC) that was developed by scientists from JPL and engineers from Cybersonics, Inc. for possible use in extraterrestrial applications [Bar-Cohen et al, 1999, Bao et al., 2003]. A novel design method is being sought for the optimization of JPL’s USDC cutting edge shape in order to maximize its drill rate. New analytical models for describing the rock/bit interaction are derived. The analytical models allow us to perform optimization of the coring bit’s geometry to maximize the drill rate.

So far, the USDC drill bit/rock interaction has been studied using Finite Element Methods to obtain the rock stress/strain distribution during penetration and estimation of the drilling rate, considering the specific energy as an intrinsic property for various rock types including basalt. The current FEM analysis of bit/rock interaction treats the drilling as a contact process, which is actually a complex penetration process. The specific energy is defined as the work done in cutting a unit volume or mass of rock, and it provides a measure of the drilling efficiency. In our new analytical models for describing the rock/bit interaction using existing rock cutting theories, the specific energy is not only an intrinsic property of rock but it is highly dependent on the bit type and design as well. The previous analysis for theoretical specific energy is appropriate to a single chisel-type drill tool. For practical percussive/vibratory type coring tools, the teeth are located on the bottom annulus of cutting edge and they affect the drill rate. The physical models of penetration considering the interaction between adjacent teeth based on two failure theories were established for the design of any percussive/vibratory type drills which use cutting teeth to excavate rock. The numerical analysis was performed based on two analytical models. The wedge angle and the spacing between adjacent teeth are important factors for specific energy minimization.

The preliminary laboratory experiments have been undertaken on a rock sample to investigate the drilling process and to study the effect of coring bit design parameters on drilling efficiency.

2 BACKGROUND

2.1 ROCK CUTTING THEORY RELATED TO PERCUSSIVE/VIBRATORY DRILLING

Theory of Wedge Penetration into Rock
The mechanism of rock cutting by percussive/vibratory drilling involves brittle failure behavior of rock, which is characterized by fracture. Rock indentation is the basic process in drilling by mechanical means. The mechanical rock drilling methods embody the principle of penetration by indentation from various geometries of the drilling/coring bit. For example, the rock cutting of USDC is accompanied by an impact of the drill bit edge. In order to improve the rock fragmentation efficiency and maximize the drill rate of percussive/vibratory type drilling tool like USDC, it is necessary to understand the physical mechanisms of rock fragmentation under an impact load. The process of rock cutting under indentation includes generally the following stages: build up of the stress field, formation of a zone of inelastic deformation (or crushed zone), surface chipping and crater formation [1].

Some theoretical studies of bit penetration of different shape into brittle material such as rock have been proposed. One theoretical study of bit and conical penetration into brittle materials is the wedge penetration model developed by Paul and Sikarskie [2], which is based on the Mohr-coulomb failure criteria. The theory is used to predict the forces and associated penetration displacements during both crushing and chipping phases. The analytical theory of static penetration can be used for the analysis of a single wedge-shape tooth. We focus on predicting the force-penetration characteristic and energy consumption behavior for harder rocks such as basalt and granite, which exhibit both crushing and chipping phase in the penetration process. Figure 1 shows the typical experimental force-penetration of percussive bit penetration that exhibit crushing and chipping modes, elastic deformation by the lines of positive slope, and regions of chip formation by those of negative slope. Points P1, P2 and P3 indicate peak values. Paul and Sikarskie compared their theoretical results with force-penetration data of charcoal grey granite by Reichmuth [3] and the general qualitative agreement is good. However, according to that theory, the peaks should lie on one straight line which is not borne out experimentally.

![Figure 1: Shape of Experimental Force-Penetration Curve](image)

**Extension Strain Failure Criterion for Rock Crack Formation**

Unlike the other failure theories, the extension strain criterion takes into account the effects of all principle stresses [4]. The theory can be applied when all the principle stresses are compressive, as occurs in the case of wedge bit loading. According to this theory, fracture of brittle rocks will be initiated when the total extension principle strain \(e_1\) in the rock, which is calculated from the classical Hooke’s Law, exceeds the critical value \(e_c\) of the rock type:

\[
e_1 > e_c
\]

**Tensile Splitting Theory Applied to Rock Excavation**

The tensile splitting theory developed by Evans and Murrell to describe the basic mechanics of coal cutting [5] was adapted to rock excavation by Roxborough [6]. Figure 2 shows the idealized tensile fracture theory developed by Evans (1962) for a wedge penetration into coal. In their analysis, the effect of friction is neglected and the width of wedge is considered. Three different materials, anhydrite, limestone and sandstone, were tested and proved to conform well to the theoretical predictions of tensile failures.

![Figure 2: Force Diagram According to Evans (1962)](image)

Most of the analytical and experimental studies of bit penetration into brittle material are appropriate to a single chisel-type drilling tool. In many practical percussive/vibratory rock coring tools, like USDC, the cutting teeth array is put on the bottom annulus of cutting edge as shown in Figure (see Figure 3 right). At this case, it is interesting to know if there is the possibility of exploiting the interaction effect that one tooth may have on its neighbor and how it will affect the drilling rate of coring bit. Roxborough [6] directly applied the total thrust force formula P for simplified tensile breakage model to derive specific energy considering interaction between cutting teeth, which is not applicable for bit cutting process of percussive and vibratory drilling, like USDC. Our focus is to find out the possibility to derive an optimal spacing between two teeth in order to achieve an optimal specific energy for the coring bit with cutting teeth array.

Wang developed a mathematical rock failure model using finite element method to describe the details of chip formation and provide quantitative evaluation of the stress and displacement field during the penetration process [7]. But the simulation did not study the effect of tool parameters on specific energy, which is a meaningful measure of drilling efficiency.

**2.2 USDC BACKGROUND**

The ultrasonic/sonic driller/corer (USDC) device [Bar-Cohen et al, 1999, Bao et al., 2003]. consists of three main components: an ultrasonic transducer (piezoelectric stacks, a backing element and a horn), free mass and drill stem (Figure 3 left). The actuator operates as a hammering mechanism that hits the free mass and in turn hits the bit, which fractures the target rock. The actuator consists of a piezoelectric stack with backing for forward power delivery and a horn for amplification of the induced displacement. The impacts of the free mass create stress pulses that propagate to the interface of the bit and the rock onto which the USDC is placed in contact. The rock is fractured when its ultimate strain is exceeded at the rock/bit interface [8].
3 THEORETICAL ANALYSIS

3.1 RESEARCH APPROACH

In USDC, the free mass impacts a drill stem, transferring its momentum and energy to the drill stem in the form of a stress wave [8]. The stress wave is then transmitted along the drill stem to the bit-rock interface, where the stress level is raised sufficiently by the bit edge shape to cause rock failure and bit penetration. The effect of drill stem parameters, bit parameters and bit edge shape on the specific energy is studied analytically in our work. Based on the analysis of the analytical modeling, an approach for optimizing the shape of the coring bit so that the drill rate is maximized will be derived.

In order to improve the rock fragmentation efficiency and maximize the drill rate of USDC, we are using the energy balance analysis between the rock and the drill bit resulting in Equation (2):

\[ R = \frac{\eta P_0}{AE} \]  

(2)

Where \( R \) is the drill rate, \( P_0 \) is the power output of the drill, \( \eta \) is the drill-to-rock power transmission efficiency, \( A \) is the hole cross-section area and \( E \) is the specific energy.

Based on Equation (2), the following ways can be taken:

1) Minimize the specific energy \( E \) by considering the rock fracture process during the bit penetration, in order to raise the impact stress level to break the rock. Here the specific energy is considered not only an intrinsic property of the rock but is highly dependent on the bit type and design as well.

2) Maximize the drill-to-rock power transmission efficiency \( \eta \), in order to increase the energy transmitted to the rock. The stress wave generated by the free mass in the drill stem travels to the bit edge/rock interface. Part of the energy in wave goes into the rock breaking and part is reflected.

Then perform drilling experiments to validate the theoretical analysis and study the influence of coring bit design variables on cutting efficiency.

3.2 ESTABLISHING THE USDC CORING BIT CUTTING EDGE MODEL

The USDC coring bit inside diameter (ID) is about 10 mm while the wall thickness is about 0.5 mm. The cutting edge can be an array of teeth of wedge, conical or hemispherical shape, along the bottom annulus. The wedge-shape cutting edge is studied in this work (see Figure 3 Right).

Here we focus on deriving the specific energy for coring bit into rock with wedge-shape cutting array. Since different failure patterns were observed in practical and laboratory drilling, two failure modes were assumed to develop the penetration model considering the interaction between two adjacent teeth, based on two failure theories, Coulomb-Mohr failure criterion and tensile splitting theory.

3.3 SPECIFIC ENERGY FORMULATION USING COULOMB-MOHRS FAILURE THEORY

The penetration model of a single rigid wedge-shape tooth into brittle rock is shown in Figure 4. Where \( d_i \) is the penetration in the \( i \)th cycle; \( d_{i+1} \) is the penetration at formation of the \( i+1 \)th tooth; \( \theta \) is equal to half the single tooth wedge angle; \( \psi \) is the failure angle of the chips; \( P_{i+1} \) is the wedge force during the \( i+1 \)st cycle.

As the wedge advances, the rock is fragmented in some local region surrounding the wedge and the elastic stress builds up. When a certain penetration level \( d_{i+1} \) is reached, then the stresses along the fracture surface are sufficient to cause failure and a chip is formed. The rock exhibits both crushing and chipping phases in the penetration process. Chip failure is assumed to occur along planes extending from the wedge tip to the free surface at the failure angle \( \psi \).

Where \( \tau \) is the shear stress on the fracture surface; \( \sigma \) is the normal stress on the fracture plane; \( \mu \) is the coefficient of internal friction (material parameter); \( c \) is the cohesive strength of rock. Consider the averaged force equilibrium of the \( i+1 \)st chip shown in Figure 5, and assume that the wedge rock interface is frictionless, then a stress averaged form of the criterion is used:

\[ \left| \tau \right| - \mu \sigma = c \]  

(3)

Where \( \tau \) is the shear stress on the fracture surface; \( \sigma \) is the normal stress on the fracture plane; \( \mu \) is the coefficient of internal friction (material parameter); \( c \) is the cohesive strength of rock. Consider the averaged force equilibrium of the \( i+1 \)st chip shown in Figure 5, and assume that the wedge rock interface is frictionless, then a stress averaged form of the criterion is used:

\[ \left| \tau \right| - \mu \bar{\sigma} = c \]  

(4)

Where \( \bar{\sigma} = T / L \), and \( \bar{\sigma} = N / L \).

Figure 4: Single Wedge Tooth Penetration Model

The Coulomb-Mohr yield condition is satisfied along the fracture line and failure occurs when the maximum value of virtual shear stress equals the cohesive strength \( c \):

Figure 5: Mechanical Analysis of the \( i+1 \)st Chip

In the formulation of the force-penetration relation by Paul [2], two types of testing conditions, constant rate and constant
load, were assumed to provide approximate bounds on the actual loading condition.

For constant rate load model, the specific energy is given by:

\[ E_a = \frac{kK}{2(k - K)} \tan \psi \]

(5)

For constant load model, the specific energy is given by:

\[ E_b = \frac{K[(k - K)^2 + k^2]}{2k(k - K)} \tan \psi \]

(6)

3.4 INTERACTION ANALYSIS USING COULOMB-MOHR FAILURE THEORY

The above analysis for theoretical specific energy is appropriate to a single chisel-type drill tool. Here we extended Paul’s theory and derive the specific energy formulation considering the interaction between adjacent teeth, in order to study the effect of spacing between the teeth on the specific energy and chipping mechanism. The physical model of the chipping process considering the interaction between adjacent teeth is shown in Figure 6, where: \( \psi \) is the failure angle; \( d_{i+1}^* \) is the depth of cut; \( s \) is the spacing between the teeth. Figure 6 shows the critical condition where the interaction between two chips will occur. From geometric analysis, the interaction will occur when:

\[ 2d_{i+1}^* \cot \psi \geq s \]

(7)

Combined with the above specific energy formulations, Eq. (5) and (6), it is possible to study how the specific energy varies as a function of the teeth spacing and number of teeth.

3.5 SPECIFIC ENERGY FORMULATION USING TENSILE SPLITTING THEORY

The preliminary theory of tensile breakage developed by Evan [5] for ploughing of brittle material can be extended to rock drilling process. Figure 7 illustrates the assumed idealized penetration model by tensile fracture for a coring bit into rock considering the interaction between adjacent teeth. Figure 7 shows the critical condition where the interaction between two teeth will occur, where the two failure lines oe and oa meet and “big” chip oabdeo is generated. It is assumed that failure is caused by tearing of the rock along curves oe and oa. It is also assumed that the arcs of failure oe and oa are circular and tangential at the wedge tip e and a. The failure curves are assumed to have equal radius r. The angle oo'e is 2a. Consider the left-side chip odeo. It is assumed that there is no friction between the tooth and the rock.

Here we just consider the equilibrium of the left part odeo of whole chip. The forces acting on the part odeo are:

1. The force \( R' \) acting normal to the surface of the tooth de; and
2. The resultant \( T \) of the tensile forces acting at right angle to line oe.

A third force is required to maintain equilibrium in this part. From the Statics theory “for the equilibrium state of a body under the action of three forces, the lines of action of the three forces must be concurrent”, it can be assumed the third force \( S \) acts through o and all the forces are shown in Figure. The third force \( S \) can be thought of applied by the right-side chip oabco.

\[ T = tr \int_{-\alpha}^{\alpha} \cos \alpha d\alpha = 2tr \sin \alpha \]

(8)

Taking moments about o:

\[ R'[2r \sin \alpha \sin \left(\frac{\pi}{2} - \alpha - \theta\right) + \frac{h_1}{2\cos \theta}] = 2tr \sin \alpha \cdot r \sin \alpha \]

(9)

There exists a geometric relation:

\[ 2r \sin \alpha \cdot \sin \alpha = d \]

(10)

Eliminating \( r \) between equations (9) and (10), we can get an expression for \( R' \):

\[ R' = \frac{td^2}{\sin \alpha 2d \cos(\alpha + \theta) \cos \theta + h_1 \sin \alpha} \]

(11)
R' has two components H’ and V’. Owing to the symmetry of the forces acting on the wedge the total vertical cutting force P on the wedge is equal to 2 V’. Hence the total cutting force on the wedge:

\[
P = \frac{td^2 \sin 2\theta}{\sin \alpha [2d \cos(\alpha + \theta) \cos \theta + h_1 \sin \alpha]} \tag{12}
\]

Where \( P \) = cutting force of wedge into rock at the instant of failure; \( t \) = tensile strength of rock; \( h_1 \) = drilling depth; \( \theta \) = half wedge angle; \( d \) = half spacing between two teeth, \( s = 2d \).

The angle \( \alpha \) is obtained in terms of the other angle \( \theta \) by means of an hypothesis of minimum work, i.e.,

\[
\frac{\partial P}{\partial \alpha} = 0 \tag{13}
\]

Giving

\[
2d \cos \theta \cos(2\alpha + \theta) + h_1 \sin 2\alpha = 0 \tag{14}
\]

Solving this equation using Maple, we get:

\[
\alpha = f(\theta) = \frac{1}{2} \arctan \frac{2d \cos^2 \theta}{-h_1 + d \sin 2\theta} \tag{15}
\]

From the tensile splitting theory, it can be seen the theoretical cutting force is the function of rock material properties \( t \), half wedge angle \( \theta \), drilling depth \( h_1 \) and half spacing \( d \).

3.6 INTERACTION ANALYSIS USING TENSILE SPLITTING THEORY

The developed physical model of the chipping process considering the interaction between adjacent teeth is shown in Figure. Interaction between two teeth will occur when the sidesplay produced by each tooth meet or overlap. If \( s \) is the spacing between adjacent teeth and define the spacing/depth ratio as

\[
a = \frac{s}{h_1} \tag{16}
\]

Where \( s = 2d \). Figure 7 shows the critical condition when interaction will begin to occur. Assuming cutting force \( P \) is linear with respect to depth of cut \( h_1 \), the energy performed in the penetration is:

\[
W = \frac{1}{2} Ph_1 \tag{17}
\]

As seen from Figure 7, the total volume of rock removed per unit length of cutting edge is:

\[
V = \left( dh_1 - \frac{1}{2} h_1^2 \tan \theta + \frac{1}{2} d^2 \cot \theta \right) \times 2 \tag{18}
\]

Dividing Eq. by, the specific energy when interaction occurs is:

\[
E = \frac{Ph_1}{4 \left( dh_1 - \frac{1}{2} h_1^2 \tan \theta + \frac{1}{2} d^2 \cot \theta \right)} \tag{19}
\]

Where \( \alpha \) can be obtained from Eq. (15).

4 PARAMETRIC ANALYSIS

Using the mathematical theories presented in Section 2, a parametric analysis study has been performed to identify values of important parameters of coring bit cutting edge that will minimize the specific energy.

4.1 PARAMETRIC ANALYSIS OF SINGLE WEDGE-SHAPE CUTTING EDGE MODELING

Figure 8 shows the variation of the specific energy as a function of the half wedge angle and rock properties. Three material parameters of rock must be specified in Paul’s theory: the angle of internal friction (\( \Phi \)), compressive strength (\( C \)) and the slope of force-penetration curve during (\( k \)) for a given wedge geometry. Here the pertinent parameters of charcoal grey granite for the simulation are from [2]: \( 29 = 90^\circ \); \( \Phi = 0^\circ \), 10’ and 20’; \( C = 33,000 \) psi and \( k = 400,000 \) psi. As seen from Figure 8 (a), the prediction by Coulomb-Mohr Failure theory shows that the specific energy increases with the increase of the wedge angle. With the increase of the rock internal friction angle, the specific energy profile transforms in a non-linear way.

In tensile splitting theory, the tensile strength of rock needs to be specified. Here the pertinent parameters in simulation are: Limestone - uniaxial compressive strength 16,000 – 23,200 psi and uniaxial tensile strength 990 – 1500 psi; Sandstone - uniaxial compressive strength 5,000 – 7200 psi and uniaxial tensile strength 260 – 440 psi; Michigan basalt - uniaxial compressive strength 120 MPa and uniaxial tensile strength 14.6 MPa. As seen from Figure 8 (b), the specific energy increases with the increase of wedge angle. The harder the rock, the more specific energy needed.

![Specific Energy vs Half Wedge Angle for Charcoal Grey Granite](image-url)
Figure 8: Variation of the Specific Energy as a Function of the Half Wedge Angle and the Rock Properties: a) Prediction by Coulomb-Mohr Failure theory and b) Prediction by Tensile Splitting Theory

4.2 PARAMETRIC ANALYSIS OF CORING BIT CUTTING TOOTH ARRAY

Prediction by Coulomb-Mohr Failure Theory

The interaction will start to occur when:

\[ 2d_{c1} \cot \psi = s \] (20)

Assume the spacing/depth ratio to be:

\[ a = \frac{s}{d} \] (21)

Put it into specific energy formulation, then the variation of specific energy with spacing/depth ratio can be studied. For the coring bit, the geometric relation exists for bottom edge teeth array:

\[ c = s \times n \] (22)

Where \( c \) is the average perimeter of bottom annulus, \( n \) is number of teeth. Assume the coring bit diameter and thickness, the variation of specific energy with number of teeth can be studied.

Figure 9 shows four cases for a tooth array with a wedge angle corresponding to 30°, 60°, 90° and 120° for constant load assumption, where (a) predicts the variation of the specific energy with cutting teeth spacing/depth Ratio and (b) predicts variation of the specific energy with cutting teeth numbers. Figure 10 shows the cases for constant rate assumption. Here we assume coring bit outer diameter (OD) is 0.625 inch and thickness is 0.125 inch. The rock parameters keep same values of section 3.1. Some results can be derived from the simulation. There exists an optimal range of spacing/depth ratio for specific energy at all four wedge angles. The cutting teeth interaction is expected to occur at spacing/depth ratios less than about 5 to 6 for the coring bit since after that, the specific energy will either increase or be constant. As the ratio approached zero, the specific energy increases rapidly. For a wedge angle of 90° and 120°, the minimum specific energy conditions may be achieved when the ratio is approximately 3 to 4. For the coring bits used in our laboratory drilling tests and having the dimension mentioned above, the more the number of teeth, the more specific energy needed.
Assume the spacing/depth ratio $a$ to be:

$$a = \frac{s}{h_i} \quad (23)$$

For the coring bit, the geometric relation exists for bottom edge teeth array:

$$s \times n = \pi (OD - t_1) = \pi (ID + t_1) \quad (24)$$

Where $t_1$ is the thickness of coring bit. Put the above equations into specific energy formulation, then the variation of specific energy with spacing/depth ratio can be studied. It is found out the tensile splitting theory applies only on larger wedge angles of cutting teeth. Figure 11 shows two cases for a tooth array with a wedge angle corresponding to $90^\circ$ and $120^\circ$, where (a) predicts the variation of the specific energy with cutting teeth spacing/depth Ratio and (b) predicts variation of the specific energy with cutting teeth numbers. Here we assume coring bit outer diameter (OD) is 0.625 inch and thickness is 0.125 inch. The tensile strength of limestone in simulation is 1245 psi. The cutting teeth interaction is expected to occur at spacing/depth ratios less than about 4 to 6. For a wedge angle of $90^\circ$ and $120^\circ$, the optimal teeth number is about 4 or 6 respectively for the coring bit (OD = 0.625 inch, thickness 0.125 inch) at a depth of 0.25 inch into limestone.

5 EXPERIMENTAL STUDY

In order to corroborate the above theoretical specific energy analysis for coring bit considering the interaction between adjacent teeth, we performed preliminary laboratory drilling tests under dynamic loading conditions. There are very few reported study on the experimental investigations of coring bits with cutting teeth array under the dynamic loading in percussive/vibratory type drilling. For the optimal design of USDC coring bit, it is also necessary to study the effect of bit design parameters on drilling efficiency.

5.1 EXPERIMENTAL DESIGN/APPARATUS

The complete experimental set-up is shown in Figure 12, this test system consists of controller, data acquisition system, rock samples and rock holder. Figure 13 (Left) shows the coring bit sets being built. The dimensions of coring bits are: OD = 0.625 inch, thickness 0.125 inch. Four 12-teeth, 60° wedge angle coring bits were built, while two 6-teeth, 60° wedge angle coring bits with one sharp and dull teeth were built. The teeth were machined using special double shank milling cutters under the milling machine. All the bit were manufactured of grade A2 tool steel and were heat treated following the heat treatment procedure of tool steel A2. The test rig is an Instron 8800 Servohydraulic testing machine.
which can apply dynamic loads in cyclic or ramp waveforms. In load control mode, the load amplitude and load rate can be adjusted to simulate impact. The coring bit was clamped into the upper jaw. The rock sample was attached to rock holder with Epoxy glue and the holder was clamped into lower jaw.

Force-penetration results were taken out form the data acquisition system. The energy expended in each test is the area under the force-penetration curve. The energy from the curve was calculated using Matlab. The mass of cuttings were measured using a scale with high accuracy. The ratio of the expended energy to the mass of cuttings is the specific energy, which is the energy required to break out a unit mass of rock.

Figure 12: Experimental Apparatus

Figure 13: (Left) Coring Bit Sets, (Right) Drilling Test

5.2 PRELIMINARY EXPERIMENTAL RESULTS

In this preliminary experiments, a total of 4 tests were conducted using four coring bits to drill one limestone. In order to verify our theoretical interaction analysis of cutting teeth array and compare the difference in drilling efficiency between sharp and dull teeth, total six coring bits with 60° wedge angle, three 12-teeth, one sharp 6-teeth and dull 6-teeth, were manufactured. All four tests were conducted under the same loading condition. Figure 13 (Right) shows one representative drilling process. During the tests, it was clearly seen that the coring bit with sharp 6-teeth create the largest crater volume. The pertinent experimental results for limestone are listed in Table 1. The third row displays  the specific energy for each coring bit. The energy density for 6-teeth coring bit is smaller than that of 12-teeth coring bit. Figure 14 shows the experimental load-penetration curve for 6-teeth sharp bit (red) and 6-teeth dull bit (Green) into Limestone. Figure 15 shows the experimental load-penetration curve for two 12-teeth coring bits into Limestone. It can be seen that under the same loading condition, the coring bit with 12-teeth cutting array will consume more energy than the coring bit with 6-teeth, which follows the same trend predicted by our theory.

<table>
<thead>
<tr>
<th>Coring Bits</th>
<th>6-teeth</th>
<th>6-teeth</th>
<th>12-teeth</th>
<th>12-teeth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (KN.mm)</td>
<td>21.1678</td>
<td>14.1573</td>
<td>9.5448</td>
<td>7.5545</td>
</tr>
<tr>
<td>Mass of Cuttings (g)</td>
<td>1.232</td>
<td>0.4553</td>
<td>0.323</td>
<td>0.217</td>
</tr>
<tr>
<td>Energy Density (KN.mm/g)</td>
<td>17.18</td>
<td>31.08</td>
<td>29.56</td>
<td>34.81</td>
</tr>
</tbody>
</table>

Table 1: Experimental Data for One Limestone (2θ = 60°)

Figure 14: Experimental Load-penetration Curve for 6-Teeth Sharp Bit (red) and Dull Bit (Green) into Limestone

Figure 15: Experimental Load-penetration Curves for Two 12-teeth Coring Bits into Limestone

6 CONCLUSION/DISCUSSION

This work has established an optimal design method for the coring bit with cutting teeth that penetrate brittle materials. The method developed here is applicable to tools that operate in percussive, vibratory or ultrasonic drilling using coring, chisel or hammer bits. The previous analysis for theoretical specific energy of wedge penetration is appropriate to a single chisel-type drill tool. Two analytical models based on rock fracture
mechanics were developed to describe the interaction between adjacent teeth in coring bit. The wedge penetration theory developed by Paul and Sikarskie was extended to derive the interaction model of cutting teeth and associated specific energy formula, while Evans’ theory of cutting was extended to develop the new analytical model describing the interaction effect that one tooth may have on its neighbor and associated specific energy formula.

The numerical analysis was performed based on two analytical models. The angle of wedge is an important factor for specific energy minimization. Although the sharper bit edges increase the stresses developed at the edge-rock interface and the available energy can be utilized more efficiently in rock cutting, in practice a compromise must be considered between the initial higher penetration rate made by the small wedge-angle design, and the subsequent bit edge wear as the penetration proceeds.

It is possible to derive an optimal disposition of cutting teeth, in order to achieve a minimum total specific energy for the coring bit. From extended Paul’s theory, the cutting teeth interaction is expected to occur at spacing/depth ratios less than about 5 to 6, for wedge angle 30, 60, 90 and 120 degree. The extended tensile splitting theory was used to predict the rock/bit penetration for larger wedge angle such as 90 and 120 degree. The cutting teeth interaction is expected to occur at spacing/depth ratios less than about 4 to 6. For larger wedge angle, we can design the coring bit with optimal number of teeth based on the models.

The preliminary tests using our specific built coring bit sets shows that 12-teeth coring bit used more energy than 6-teeth bit and 6-teeth coring bit with 60° wedge angle is an optimal designed coring bit. More laboratory drilling tests are conducted to verify our theoretical interaction analysis of cutting teeth array and compare the difference in drilling efficiency between optimal designed and poor designed coring bit.

The mechanical methods of rock cutting in percussive/vibratory drilling embody the principle of penetration by indentation from various geometries of the cutting tool. So far, the theories consider the penetration by symmetrical wedge-shaped cutting teeth. In order to improve the drill rate of USDC, it is good to generate the lateral vibration of bit by introducing the non-symmetrical design of cutting teeth, and the vibration helps to remove debris at the bit. The analytical models considering the non-symmetrical design of cutting teeth in coring bit will be conducted.

7 ACKNOWLEDGMENTS

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8 REFERENCES