Analysis of Tool Work Interaction in Ultrasonic Percussive Rock Abrader for Planetary Rock Abrading Applications

Rintu George Thomas*
PG Scholar, Dept. of ME
Mar Athanasius College of Engg.
Kothamangalam, Kerala

Deviprasad Varma P R
Professor, Dept. of ME
Mar Athanasius College of Engg.
Kothamangalam, Kerala

Roy N Mathews
Professor, Dept. of ME
Mar Athanasius College of Engg.
Kothamangalam, Kerala

***Abstract*—Ultrasonic percussive Rock Abrader has an abrasion tool that allows the removal of weathered layers from rock surfaces. In this paper, we conducted an analytical study of the design of abrading bits of Ultrasonic Percussive Rock Abrader which percussively penetrates the brittle rock material. It is found out that the abrading bit's specific energy is a function of the cutting tooth angle and rock material properties. There exist an optimal tooth angle and pitch depth ratio that minimizes the abrading bit's specific energy and hence maximize the rock crushing rate.**

***Keywords*— Percussion, Rock abrading, Specific energy, Tooth angle, Pitch depth ratio**

I. INTRODUCTION

Rock and soil penetration by coring, drilling or abrading is of great importance for a large number of planetary exploration applications [1]. These devices will operated from different robotic platforms or rovers, are efficient to drill various rocks including granite, diorite, basalt, limestone etc.

Ultrasonic drilling tools capable of penetrating rock are of particular interest to designers of planetary exploration missions. Traditional rotary drilling tools are difficult to employ on planetary surfaces because of the problems associated with achieving significant weight-on-bit and the torque reaction of the drill string in a low-gravity environment. Ultrasonic Percussive Rock Abrader (UPRA) is a typical ultrasonic penetrating tool, driven by a high frequency hammering action resulting from vibration, that allows for the removal of weathered layers from the planetary rock surfaces.

In this paper a design optimization methodology based on rock fracture mechanics is developed for an abrading bit with a series of cutting tooth located along the bottom face of the abrasion disk that is penetrating brittle materials like rock and ice during percussive drilling. A non linear programming model for describing the rock/bit interaction is derived and allows us to identify the abrading bit's geometry to maximize the rock crushing rate.

II. BACKGROUND

Over millions of years, rocks on Mars were subjected to various surface effects including weathering, impact of meteorites and erosion. To obtain useful information about Mars planetary, geologists are seeking to remove the outer layers (approx. 2 - 5 mm depth) from the sampled rock to get access to pristine material. For this purpose, a Rock Abrader system needs to develop to abrade a small depth in rocks as hard as basalt. An abrasion tool that allows for the removal of weathered layers from rock surfaces.

III. ULTRASONIC PERCUSSIVE ROCK ABRADER (UPRA)

Ultrasonic Percussive Rock Abrader (UPRA) is a penetration mechanism that is driven by a high frequency hammering action resulting from vibration [2]. The model being developed for the UPRA describes five elements involved in the abrading i.e., the electrical driver, piezo-electric ultrasonic actuator, free-mass, abrasion tool bit and the rock. The Schematic for UPRA is shown in Fig 1.

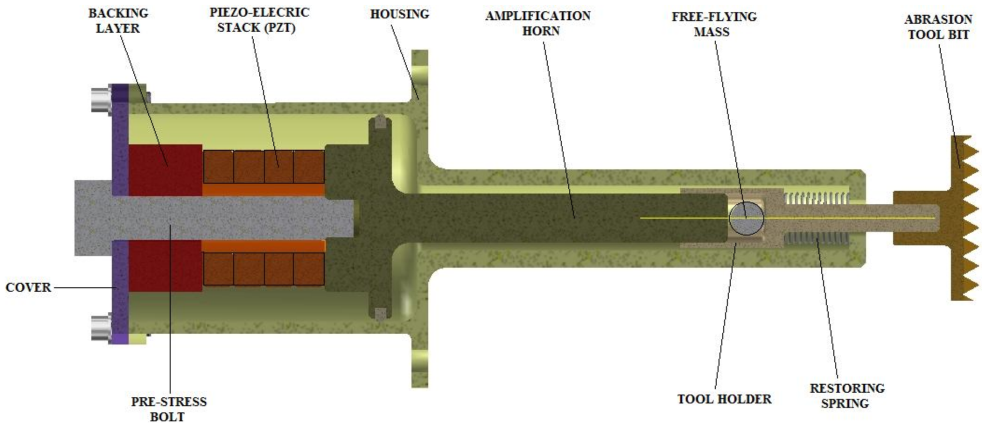

Fig 1: Schematic of Ultrasonic Percussive Rock Abrader (UPRA)

UPRA's Actuator consists of a piezoelectric stack with a backing layer for forward power delivery and a horn for amplification of the induced displacement [1]. The actuator is driven in resonance and is held in compression by a stress bolt that prevents its fracture during operation. The stack of piezoelectric material is excited at the resonance frequency of the ultrasonic actuator. Through the amplification of the ultrasonic horn, the displacement of the vibration reaches tens of microns at the tip of the horn. A free mass is contacted to the horn tip of the USDC. During drilling operation, the free mass bounces and moves back and forth between the ultrasonic horn and the drill stem.

Due to the fact that the velocity of the free mass is smaller than the velocity of the horn tip vibration, the free mass usually contacts the horn tip at a favourable phase of horn tip vibration. During which the free mass picks up momentum and is accelerated back to the drill stem [2]. The free-mass transfers impact momentum from the ultrasonic transducer to the drill stem at a sonic frequency ranging from tens of Hz to about 1000 Hz. The shock waves caused by the impacts of the free mass upon the drill stem propagate to the bit/rock interface. The impacted brittle medium (rock, ice, etc.) is fractured when its ultimate strain is exceeded at the medium/bit interface [6].

The abrasion tool being made with a 30 mm diameter disk that is attached to a shank that fits around the horn. Free mass is placed inside a shank between the horn and the bottom of the hole along the inner part of the bit. On the bottom of the disk, teeth being machined in the form of pyramidal pins that sticks out of the disk.

IV. ROCK PENETRATION IN PERCUSSION DRILLING

The mechanism of rock cutting by percussive/vibratory drilling involves brittle failure of the rock, which is characterized by fracture. Rock indentation is the basic process in drilling by mechanical means [7]. The process of rock cutting under indentation generally includes the following stages, which is shown in figure 2.

1. Build-up of the stress field.
2. Formation of a zone of inelastic deformation or crushed zone.
3. Surface chipping.
4. Crater formation.

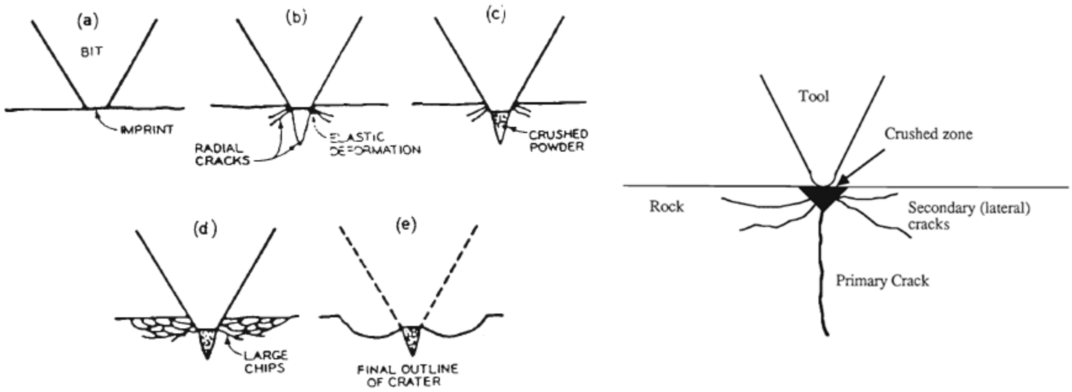

Fig 2: Sequence of crater formation and fracture patterns during percussive drilling [4].

One theoretical study of bit penetration into brittle materials is the static wedge penetration model developed by Paul and Sikarskie which is based on the Coulomb–Mohr failure theory [3]. The theory was used to predict the forces and associated penetration displacements during both crushing and chipping phases. Figure 3 shows a theoretical and experimental force–penetration curve of percussive bit penetration that exhibits crushing and chipping modes.

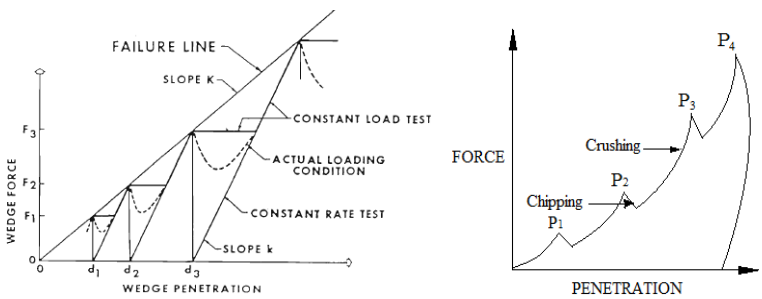

Fig 3: Theoretical and Experimental Force-Penetration curve for brittle crater model

A. Theoretical approach in rock crushing

The rate at which rock can be crushed [6], R, equals

$$R = \frac{hPi}{AE} \quad (1)$$

where R is the crushing rate, P_i is the power input of the drill, η is the drill-to-rock power transmission efficiency, A is the hole cross-section area and E is the specific energy. The crushing specific energy is defined as the work done in cutting a unit volume or mass of rock. Based on above eqn, the following two possibilities exist to maximize the crushing rate. I.e., minimize the specific energy or maximize the drill to rock power transmission efficiency. Here we consider only the minimization of specific energy.

B. Formulation of Specific energy based on Mohr-Coulomb Failure theory

The penetration model of a single rigid pyramidal or conical shaped tooth into brittle rock is shown in the following figure.

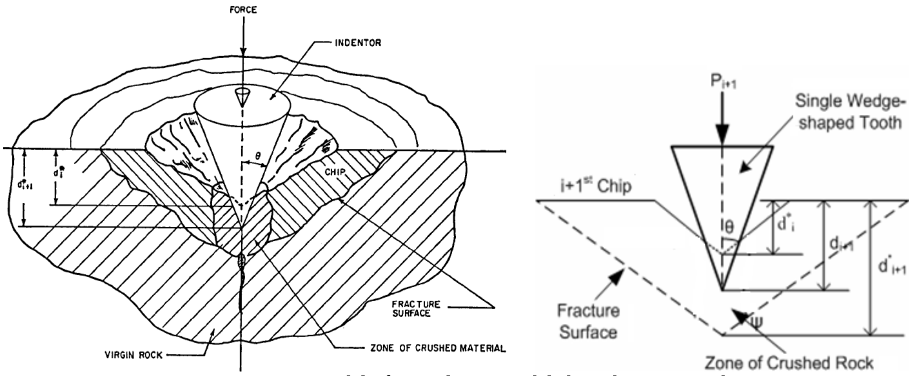

Fig 4: Penetration model of a single pyramidal shaped cutting tooth

As the tooth advances, the rock is fragmented in some local surface surrounding the tooth and the elastic stress builds From Fig 4, d_{i+1} is the penetration in the $(i+1)^{th}$, cycle; d_i and d_{i+1}^* are the penetrations at the formation of the i^{th} and $(i+1)^{th}$ chips, θ is equal to half the single tooth angle, Ψ is the failure angle of the chips and P_{i+1} is the tooth force during the i+1 cycle [3]. 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. In this model, chip failure is assumed to occur along planes extending from the tooth tip to the free surface at the failure angle Ψ.The Coulomb–Mohr yield condition is satisfied along the fracture line and failure occurs when the maximum value of the virtual shear stress equals the cohesive strength c, which is shown in the following eqn.

$$\tau - \mu\sigma = c \quad (2)$$

where τ is the shear stress on the fracture surface, σ is the normal stress on the fracture plane, μ is the coefficient of internal friction (material parameter), c is the cohesive strength of the rock and ϕ is the angle of internal friction and is related to the coefficient of friction by the following eqn.

$$\mu = \tan\phi \quad (3)$$

For frictionless cutting tooth, the failure angle of chip is given by the following eqn.

$$\Psi = \frac{\pi}{4} - \frac{\theta+\phi}{2} \quad (4)$$

Two types of ideal loading conditions, constant rate and constant load were assumed in the formulation of the force – penetration relation by Paul and Sikarskie [3]. The constant rate condition is satisfied when the cutting tooth moves into the rock at constant velocity. For the constant rate model, the specific energy is given by the following relation.

$$E_R = \frac{kK}{2(2k-K)} \tan\Psi \quad (5)$$

The constant load condition is satisfied when the load increases without variation during the crushing process. For the constant load model, the specific energy is given by the following relation.

$$E_L = \frac{K[(k-K)^2+k^2]}{2k(2k-K)} \tan\Psi \quad (6)$$

where k is the slope of the assumed force–penetration curve during crushing and K is the slope of the line connecting the peak forces of the force–penetration curve. For the case of cutting with frictionless tooth, K is given by the below eqn.

$$K = \frac{P_{i+1^*}}{d_{i+1^*}} = 2C\frac{\sin\theta(1-\sin\phi)}{1-\sin(\theta+\phi)} \quad (7)$$

where C is the material compressive strength.

C. Parametric Analysis of single pyramidal shape cutting tooth modelling

A parametric analysis has been performed to identify the values of important design parameters of the abrasion bit that will minimize the specific energy using the above mathematical formulations. The eqns. (5) and (6) are used to study the variation of the specific energy as a function of the half tooth angle and angle of internal friction. Here, the parameters of Indiana Limestone are used in simulation, which is given below.

- Material Compressive Strength (C): 10,000 Psi (pounds per square inch)
- Slope of the force-penetration curve during crushing (k): 154,900 psi
- Angle of internal friction (ϕ): Considering 0^0, 2^0 ... 20^0.

The Fig 5 shows the variation of the specific energy as a function of the half tooth angle and the rock properties for the given material (constant rate assumption). From the figure, for frictionless tooth, the Coulomb–Mohr failure theory shows that the specific energy increases with the increase of the half the tooth angle. The sharper tooth increases the stress level developed at the rock/tooth interface so that the available energy can be used more efficiently. With the increase of the rock internal friction angle, the specific energy profile obtains a nonlinear pattern.

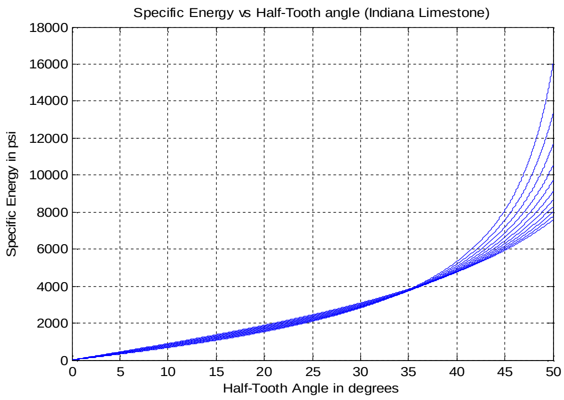

Fig 5: Variation of specific energy as a function of half tooth angle

If specific energy is criterion, zero angle is optimum. But it is not possible (structural problem). So a penalty has to be added for getting small values of θ while minimizing specific energy. Therefore θ is modified by adding a penalty term "SF/θ". An objective function is created for finding the optimum tooth angle which is given below.

$$\min_{q>0} f(q)$$

$$\text{Such that } f(q) = \left\{ \left(\frac{SF}{\theta}\right)^2 + E^2 \right\} \quad (8)$$

where SF is the structural factor. For this application and rock type, SF is taken as 1000. Since objective function is a non linear function of the design parameters, non-linear optimization is required. So a MATLAB based optimizer is developed for Carrying out optimization of θ to get minimum value of objective function. The Fig 6 shows the variation of objective function as a function of the half wedge for the given material. From the plot, we can see that objective function will minimize at a half tooth angle of 23.5^0 (corresponding to a Structural factor of 1000).

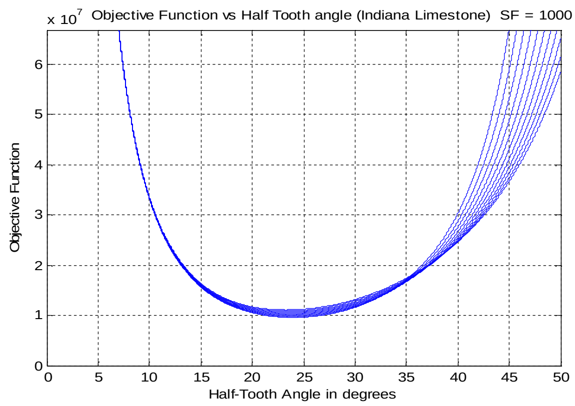

Fig 6: Variation of objective function with respect to half wedge angle

D. Parametric Analysis for Interaction between two tooth's

Considering the interaction between adjacent teeth in order to study the effect of pitch (distance between the adjacent teeth) on the specific energy and the chip formation. The physical model of penetration considering the interaction between adjacent teeth is shown in Fig. 7.

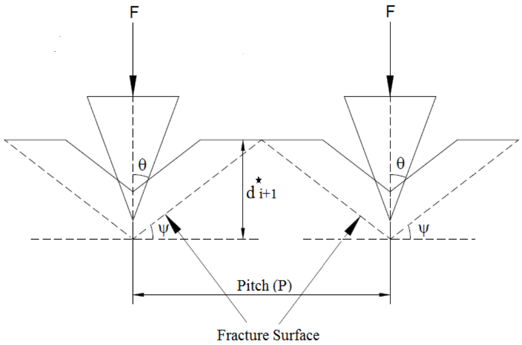

Fig 7: Physical model of interaction between adjacent teeth

The above figure shows that the teeth interaction will start when

$$2d_{i+1}^{*}\cot\Psi = P \quad (9)$$

where P is the pitch of teeth. From above, a new parameter, the pitch-depth ratio (pdr) is introduced as given below.

$$pdr = \frac{P}{di+1^{*}} \quad (10)$$

For parametric analysis, we substitute the above geometric relation into the specific energy formulations for single tooth. Fig. 8 shows the variation of the specific energy for constant rate assumption as a function of Pitch-depth ratio and rock properties for the given material.

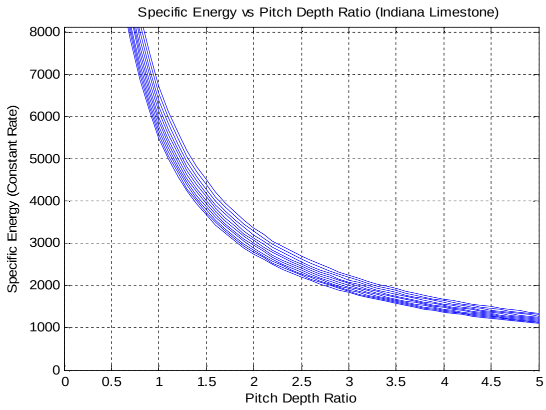

Fig 8: Variation of specific energy as a function of Pitch depth ratio

From the figure, it is clear that, when considering teeth interaction, the specific energy decreases with the increase of pitch depth ratio for both constant rate assumption. The lesser specific energy obtains at the maximum pdr value. But a large pdr value is not practically feasible. So a penalty has to be added for getting small values of pitch depth ratio, while minimizing specific energy. Therefore "pdr" is modified by adding a penalty term "(PF∗pdr)", where PF is the pitch factor. An objective function is created for finding the optimum pitch depth ratio and half tooth angle as given below.

$$\underset{0<pdr<5}{\text{Min}}\ f(\text{pdr})$$

$$\text{Such that } f(\text{pdr}) = \{(\text{PF} * \text{pdr})^2 + \text{E}^2\} \quad (11)$$

Since objective function is an unconstrained non linear function of the design parameters, non-linear optimization is required. So here also, a MATLAB based optimizer is developed for carrying out optimization of pdr value to get the minimum value of objective function. Fig. 9 shows the variation of objective function with respect to Pitch depth ratio for the given rock material having constant rate assumptions. The minimum obj. function is obtained for a teeth interaction (pitch factor of 1000) corresponds to a pdr value of 4.3.

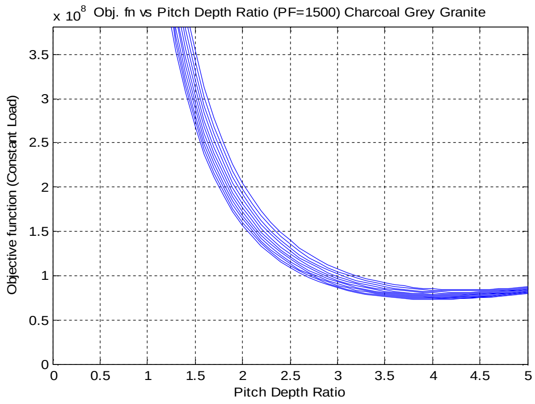

Fig 9: Variation of objective function with respect to Pitch depth ratio

V. CONCLUSIONS

This paper presents a parametric analysis of abrading bits for an ultrasonically actuated rock abrader system to be used in future interplanetary exploration drilling applications. It involves the design of abrading bits with cutting teeth array that penetrate brittle materials. From the parametric analysis, it is found out that tooth angle and pitch depth ratio are the important factors for the specific energy minimization and hence crushing rate maximization. In this model for describing the rock/bit interaction, the specific energy is assumed not only an intrinsic property of the rock but it is highly dependent on the bit geometry and design.

REFERENCES

[1] P. Harkness, M. Lucas, A. Cardoni, and L. Waugh, “Optimization of the horn, free-mass, and support architecture of a solid ultrasonic rock coring system,” in *AIAA Space 2010 Conf.*, Anaheim, CA, 2010, art. no. AIAA-2010-8765.

[2] Yoseph Bar-Cohen, Z. Chang, S. Sherrit, M. Badescu, and X. Bao, “The ultrasonic/sonic driller/corer (USDC) as a subsurface drill, sample and lab-on-a-drill for planetary exploration applications,” in *SPIE Smart Structures Conf.*, San Diego, CA, 2005, pp. 152–159.

[3] Paul, B., and Sikarskie, D. L., 1965, “A Preliminary Model for Wedge Penetration in Brittle Materials,” Trans. Am. Inst.Mine Eng., 232, pp. 373–383.

[4] Mishnaevsky JR, L.L., “Physical Mechanisms of Hard Rock Fragmentation Under Mechanical Loading: A Review,” *International Journal of Rock Mechanics and Mining Sciences*, Vol. 32, No. 8, pp.763-766, 1995.

[5] Karanam U.M. R. and B. Misra, *Principles of Rock Drilling*, A.A. Balkema/Rotterdam/Brookfield, 1998.

[6] Bao X., Y. Bar-Cohen, Z. Chang, B. P. Dolgin, S. Sherrit, D. S. Pal, S. Du, and T. Peterson, "Modeling and Computer Simulation of Ultrasonic/Sonic Driller/Corer (USDC)," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control (UFFC)*, Vol. 50, No. 9, (Sept. 2003), pp. 1147-1160.

[7] Wang, J.K., “Bit Penetration into Rock – a Finite Element Study,” *International Journal of Rock Mechanics and Mining Sciences*, Vol. 13, pp. 11 -16 (1976).

[8] F. Bell, *Engineering Properties of Soils and Rocks*. New York, NY: Wiley, 2000.

[9] Maurer and William G., “Novel Drilling Techniques”, Pearson Pub.1968.

[10] Yoseph Bar-Cohen and Kris Zacny, “Drilling in Extreme Environments: Penetration and Sampling on Earth and other Planets”, Weinheim: WILEY VCH Verlag & Co. KGaA, 2009.

[11] Yinghui Liu, Yoseph Bar-Cohen, Zensheu Chang, “Analytical and Experimental Study of Determining the Optimal Number of Wedge Shape Cutting Teeth in Coring Bits Used in Percussive Drilling”, Transactions of the ASME, August 2007.

[12] Patrick Harkness, Margaret Lucas, and Andrea Cardoni, “Maximization of the Effective Impulse Delivered by a High-Frequency/Low- Frequency Planetary Drill Tool”, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 58, no. 11, November 2011.

[13] Qiquan Quan, He Li, Shengyuan Jiang, “A Piezoelectric-driven Ultrasonic/sonic Driller for Planetary Exploration”, Proceeding of the IEEE International Conference on Robotics and Biomimetics (ROBIO) Shenzhen, China, December 2013.

C. Potthast, J. Twiefel, and J. Wallaschek, “Modelling approaches for an ultrasonic percussion drill”, Journal of Sound and Vibration, pp.405- 417, 2007.

