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Mechanical specific energy versus depth of cut in rock cutting and drilling

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ABSTRACT

The relationship between Mechanical Specific Energy (MSE) and the Rate of Penetration (ROP), or equivalently the depth of cut per revolution, provides an important measure for strategizing a drilling operation. This study explores how MSE evolves with depth of cut, and presents a concerted effort that encompasses analytical, computational and experimental approaches. A simple model for the relationship between MSE and cutting depth is first derived with consideration of the wear progression of a circular cutter. This is an extension of Detournay and Defourny's phenomenological cutting model. Wear is modeled as a flat contact area at the bottom of a cutter referred to as a wear flat, and that wear flat in the past is often considered to be fixed during cutting. But during a drilling operation by a full bit that consists of multiple circular cutters, the wear flat length may increase because of various wear mechanisms involved. The wear progression of cutters generally results in reduced efficiency with either increased MSE or decreased ROP. Also, an accurate estimate of removed rock volume is found important for the evaluation of MSE. The derived model is compared with experiment results from a single circular cutter, for cutting soft rock under ambient pressure with actual depth measured through a micrometer, and for cutting high strength rock under high pressure with actual cutting area measured by a confocal microscope. Finally, the model is employed to interpret the evolution of MSE with depth of cut for a full drilling bit under confining pressure. The general form of equation of the developed model is found to describe well the experiment data and can be applied to interpret the drilling data for a full bit.

1. Introduction

Mechanical Specific Energy (MSE) and Rate of Penetration (ROP) are two key factors for evaluating the efficiency of a drilling process. MSE is defined as the energy required to remove a unit volume of rock.[1] ROP generally refers to the depth of cut per unit time and it is proportional to the depth of cut per revolution which is equivalent to the depth of cut for a single cutter.[2] In rock cutting, modes of failure would transit from ductile to brittle as the depth of cutting increases,[3,4] and this study is focused on ductile failure mode of shallow cutting which is encountered in most of the cutting and drilling operations. Most laboratory experiments have been focused on evaluating MSE and ROP separately, to maximize ROP or to minimize MSE through investigating the influence of rock properties and operation conditions.[5–9] Recent work shows that it is more effective to strategize the drilling operation by combining these two parameters. For example, the real-time surveillance of MSE is effective for optimizing ROP.[10,11] Also, extensive experiment results show that the MSE generally decreases with ROP,[12–15] indicating the possibility to maximize ROP and minimize MSE simultaneously.

The purpose of this study is to establish a simple mathematical model between MSE and depth of cut, to facilitate strategizing a drilling process. A phenomenological cutting model developed by Detournay and Defourny explains well the physics of the decrease of MSE with depth of cut in rock cutting with the incorporation of wear mechanics.[2] Specifically, the wear introduces a flat contact area at the bottom of a cutter referred to as a wear flat, and that wear flat is considered to be fixed during a cutting. But during a drilling operation by a full bit that consists of multiple circular cutters, the wear flat length may increase because of various wear mechanisms.[16–18] The wear progression of cutters generally results in reduced efficiency with either increased MSE[19,20] or decreased ROP.[6,7,21] Thus, this study further takes into account the evolution of wear during cutting. This study focuses only on drag bits such as Polycrystalline Diamond Compact (PDC) bits.

For a single cutter, the relationship between MSE and depth of cut may be obtained in two different ways. One approach uses a suite of cutting tests and each of the test is of a fixed cutting depth when the cutter advances forward at a fixed speed. The other approach uses just a

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single cutting test with the cutting depth steadily increases by advancing the cutter both horizontally and vertically at their respective fixed speeds. The latter approach is similar to a drill-on or drill-off test in which the depth of cut varies linearly in a single test,[10,22] and it is a more convenient way to obtain the relationship between MSE and depth of cut. Both types of tests are analyzed in this study.

A simple model for the relationship between MSE and cutting depth is first derived by considering the wear progression of a circular cutter. The importance of an accurate estimate of removed rock volume for the evaluation of MSE is then illustrated through Finite Element Method (FEM) modeling. The model is further compared with cutting experiment results from a single circular cutter, for cutting soft rock under ambient pressure with actual depth measured through a micrometer,[23] and for cutting high strength rock under high pressure with actual cutting area measured by a confocal microscope.[24,25] Finally, the model is employed to interpret the evolution of MSE with depth of cut for a full drilling bit under confining pressure.[14]

2. A model of MSE versus depth of cut

2.1. Detournay and Defourny's model

Detournay and Defourny's phenomenological cutting model is derived from a consideration that the bit-rock interaction is characterized by the coexistence of cutting and frictional contact.[2] The phenomenological model is simple and yet explains well the drilling action of drag bits. The essence of the model can be explained by examining the forces acting on a cutter as illustrated in Fig. 1. For a sharp cutter, the force transmitted through a cutter is utilized in cutting rocks, and is denoted as cutting force, F^c, while for a blunt cutter, part of the force exerted onto the cutter is utilized in overcoming friction which is denoted as F^f. The mechanism with which the friction is transmitted of a blunt cutter

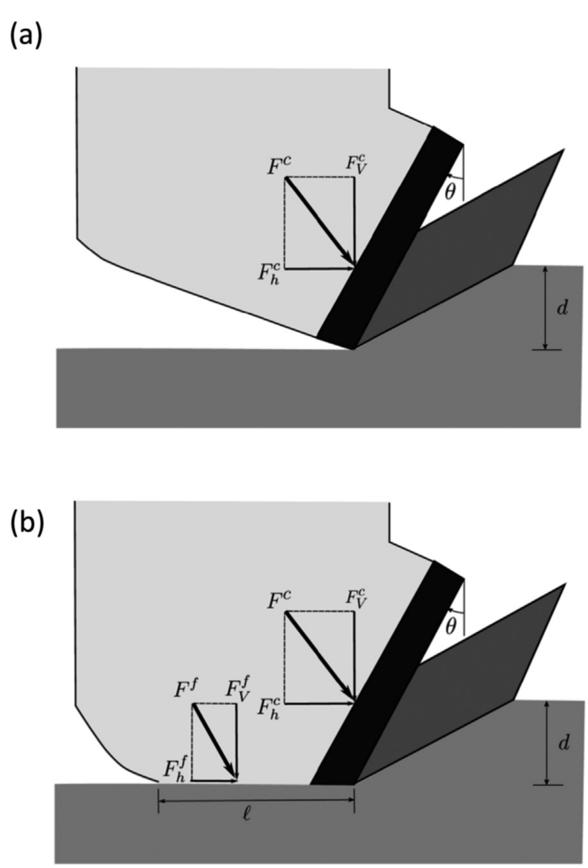

Fig. 1. Forces considered in the phenomenological model for a shallow rectangular cut: (a) A sharp cutter, (b) A blunt cutter.[2]

due to wear is effectively modeled by introducing a wear flat to the cutter. For a sharp rectangular cutter, the MSE, E, for a specific depth of cut can be written as,

$$E = \frac{F_h^c}{A_c} \tag{1}$$

where F_h^c is the horizontal component of the cutting force, and A_c is the cutting area which is the cutting width, w, multiplied by the cutting depth, d. E so obtained is a reflection of rock properties, and is referred to as intrinsic specific energy, ε. For a blunt cutter, the additional force transmitted F^f acts on the wear flat that has an area of A_f. Let the coefficient friction of the wear against the rock be μ, the normal force transmits through the wear flat is F_v^f, which can be further written as a contact stress σ multiplied by A_f, then MSE for a blunt cutter can be found as,

$$E = \frac{F_h^c + F_h^f}{A_c} = \varepsilon + \mu\sigma\frac{A_f}{A_c} \tag{2}$$

where $F_h^f = \mu F_v^f = \mu\sigma A_f$.

The contribution of the vertical force transmitted through the cutter, or the weight on bit, is reflected in the term denoted as the drilling strength, S, as follows,

$$S = \frac{F_v^c + F_v^f}{A_c} \tag{3}$$

For a rectangular cutter that is at least as wide as the rock sample, the contact friction at wear flat can be obtained from the *E-S* diagram. In an *E-S* diagram, each fixed depth cut test gives a single (S, E) data point. For a sharp cutter the data from a suite of tests plotted in an *E-S* diagram will cluster around a single point, while for a blunt cutter it they would fall on a straight line. In the case of rectilinear cut, the slope of the line is a good estimate of μ.[2] Moreover, data from the shallower depths of cut lie at the higher end of the line, while those from the deeper cuts the lower end. In other words, the MSE decreases with depth of cut.

It is convenient to normalize the MSE, or E, of Eq. (2) with respect to some strength measure of the rock. Under ambient pressure conditions, the unconfined compressive strength of rock is a convenient measure. This is especially the case as extensive experiment data under ambient pressure condition for rectangular slab cuts show that the intrinsic specific energy ε is approximately equal to the unconfined compressive strength of rock σ_c,[26–28] and after normalization Eq. (2) can be expressed as:

$$\Sigma = \gamma_0 + \mu\Pi\frac{A_f}{A_c} \tag{4}$$

where Σ and Π are the dimensionless MSE and dimensionless contact stress defined as $\Sigma = E/\sigma_c$ and $\Pi = \sigma/\sigma_c$, respectively, and γ_0 represents the normalized energy consumed on the cutting face with $\gamma_0 = \varepsilon/\sigma_c \simeq 1$ for a rectilinear cutting under ambient pressure.

The MSE for a blunt cutter is strongly affected by the contact stress on the wear flat, and the frictional contact process can be idealized as a rigid blunt tool sliding on a cohesive-frictional rock.[29] The dimensionless contact stress Π is predominantly governed by a dimensionless parameter $\eta = E_o \tan\beta/\sigma_c$, where E_o is the plane strain elastic modulus, and β denotes the inclination angle of the wear flat. The frictional contact generally includes three regimes: elastic if η is small, rigid-plastic if η is large, and elastoplastic if η is between these two limiting behaviors.[29,31] The dimensionless contact stress Π reaches its limiting value Π_* in the rigid-plastic regime, and Π_* is of order $O(1)$ and it is around two when the interface friction angle is identical to the internal friction angle under ambient pressure. Π_* increases with decreasing interface friction angle for a fixed internal friction angle.[30,31]

At a depth of cut, d, for a rectangular cutter with a width of w, $A_c = wd$ while $A_f = w\ell$ with ℓ being the length of the wear flat. The