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Energy efficiency in rock cutting

S. S. Mostafavi[1], R. H. Bao[1], L. C. Zhang*[1], J. Lunn[2] and C. Melmeth[2]

This paper proposes a simple analytical model for an optimal geometry design of a cutting pick with the criteria of greater energy efficiency. Formulation of the total energy consumption and elastic strain energy which contributes to chipping was developed for indentation or symmetrical cutting condition based on the cavity model. The ratio of the elastic strain energy to the total energy was introduced as a measure of the energy efficiency. It was found that the energy efficiency of a cutting tip depends on the tip geometry and the properties of a material to cut. For the case of a symmetric cutting, varying with the semi-apex angle of the pick, 7–25% of the total energy in cutting contributes to chipping and the rest is consumed by undesired deformation. For materials with higher *E* or smaller *Y*, the energy efficiency is lower.

Keywords: Rock cutting pick, Cavity model, Energy efficiency, Indentation

Introduction

Efficient coal/rock excavation in terms of less energy consumption has drawn wide attention. Extensive research has been carried out to find the optimised geometrical parameters of cutting picks and to develop more efficient mechanical fragmentation techniques. Designing a high performance cutting pick requires a comprehensive consideration including energy consumption, fragment size, tool fracture probability, tool life and wear. There are different geometries for the picks but which is better depends on many factors such as properties of the material to cut, depth and speed of cutting, and manufacturing costs.[1–3] To date, most studies have been based on limited number of laboratory tests.

The fracture process in rock/coal cutting is similar to an edge chipping/indentation. A pick (or indenter) indenting into a brittle material such as a rock creates a zone of highly fractured and an inelastically deformed zone beneath the indenter, called a crushed zone. As the indentation proceeds the crushed zone expands until radian–median cracks are initiated. These cracks propagate downward, in parallel to the front surface, to form a half penny crack which eventually makes chipping occur.[4] Investigations have shown that only a small percentage of the total energy during such an indentation is for chipping, because most of them is consumed in forming the crushed zone and creating excessive dusts which results in causing pollution and increasing the risk of ignition. Some researchers have found experimentally that the percentage of the energy consumed by the crushing deformation was about 70–85% of the total energy.[5] Some others[6–8] reported that this percentage was about 82–98%. On the other hand, it was claimed that the size of the crushed zone could influence the stress intensity factor and fragment size because the driving force of the crack initiation comes from the elastic deformation due to the accommodation of the crushed zone.[9] However, a clear understanding of the process is unavailable. The purpose of the present study is to establish a close form formula to understand more deeply the deformation in rock/coal indentation, and to provide a guideline for an optimal design of the pick geometry.

Energy efficiency

Based on some observations in hardness experiments, Bishop (1945), Marsh (1964) and Johnson (1970, 1985) proposed and developed cavity expansion models to study analytically the process of indentation of a rigid body into a semi-infinite specimen.[10] They assumed, as shown in Fig. 1, that there are three distinct zones beneath the indenter: (1) a core of radius a under hydrostatic stress; (2) a plastic hemispherical shell between a and c, where c is the radius of the plastic zone; and (3) an elastic region beyond radius c, where cracks initiate and propagate. The fundamental points here are (1) the hydrostatic pressure in the core must be equal to the radial component of the stress in the external zone, and (2) the radial displacement of the particles on the boundary between the core and plastic zone du, during an increment of penetration dh, must accommodate the volume of the material displaced by the indenter.

By ignoring the elastic deformation of the cavity, the ratio of the elastic strain energy in the elastic zone Ue, which contributes to the crack formation and chipping, to the total energy Ut defines the efficiency of cutting in terms of the energy consumption (U_e/U_t).

The total energy or the external work done by conical indenter Ut at the penetration depth $h=\delta$ can be calculated using the following equations

$$U_t = \int_0^{\delta} F \mathrm{d}h \quad (1)$$

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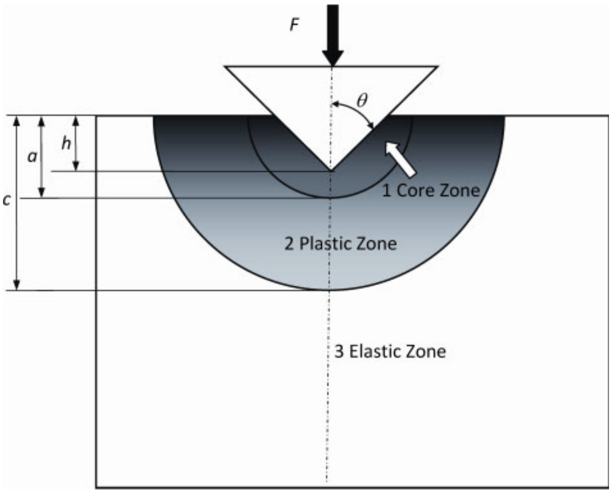


1 Different zones created beneath indenter based on cavity model

$$F = p\pi a^2,\ a = h\tan\theta \tag{2}$$

where p is the indentation pressure which in this case is equal to the hydrostatic pressure in the cavity zone, a is the radius of contact (assuming that there is no material pile-up or sink-in around indenter) which is identical to the radius of the core, and θ is the semi-apex angle of the indenter as shown in Fig. 1. The elastic strain energy outside the plastic zone is given by

$$U_e = 2\pi \int_c^{\infty} \left(\sum_{i=1}^{3} \sigma_i^e \varepsilon_i^e \right) R^2 \mathrm{d}R \tag{3}$$

where σ_i^e and ε_i^e are the components of the elastic stress and strain in the elastic zone and R is the radial distance from the centre of indentation.

The elastic–plastic solution of cavity model depends on the yield criterion used in the model. In most of the applications of cavity model in indentation and hardness test, the Tresca yield criterion was used

$$\sigma_1 - \sigma_3 = Y \tag{4}$$

where σ_1 and σ_3 are the maximum and minimum principal stresses respectively and Y is the yield stress. The equilibrium of an element of the spherical cavity in its radial direction leads to[11]

$$2(\sigma_\theta - \sigma_R) = R\frac{\mathrm{d}\sigma_R}{\mathrm{d}R} \tag{5}$$

which is subjected to two boundary conditions

$$\sigma_R|_{R=a} = -p,\ \sigma_R|_{R=\infty} = 0 \tag{6}$$

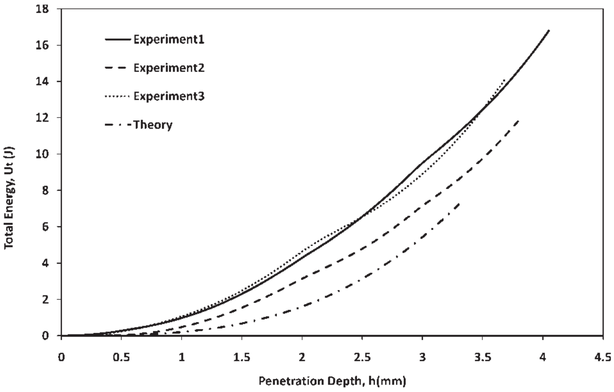
Substituting equation (4) into equation (5) results in the following relation for the radial stress in the plastic zone[11]

$$\sigma_R = 2Y\ \ln\ R + A \tag{7}$$

where A is a constant to be determined. For the elastic stresses in the elastic zone, we have[12]

$$\sigma_R = B\left(\frac{c}{R}\right)^3,\ \sigma_\theta = -\frac{1}{2}B\left(\frac{c}{R}\right)^3 \tag{8}$$

The continuity of the stress components at the elastic–plastic interface $R=c$ can be used to determine A and B



2 Total energy of indentation versus penetration depth on sandstone

as

$$A = -2Y\ \ln\ c - \frac{2Y}{3},\ B = \frac{2Y}{3} \tag{9}$$

The strains in the elastic zone can be calculated using Hooke's stress–strain relation

$$\varepsilon_R = \frac{1}{E}(\sigma_R - 2v\sigma_\theta) = -\frac{1+v}{E}\frac{2Yc^3}{3R^3} \tag{10}$$

$$\varepsilon_\theta = \frac{1}{E}[\sigma_\theta - v(\sigma_\theta + \sigma_R)] = \frac{1+v}{2E}\frac{2Yc^3}{3R^3} \tag{11}$$

By substituting $R=a$ into equation (7), the internal pressure p in the cavity which is needed to produce plastic flow to radius c is[12]

$$p = 2Y\ \ln\left(\frac{c}{a}\right) + \frac{2Y}{3} \tag{12}$$

Then the strain energy in the elastic zone and the total energy can be obtained by substituting equations (8)–(12) into equations (3) and (1), which gives rise to

$$U_e = 4\pi\frac{1+v}{E}\left(\frac{Y}{2+\alpha}\right)^2 c^3 \tag{13}$$

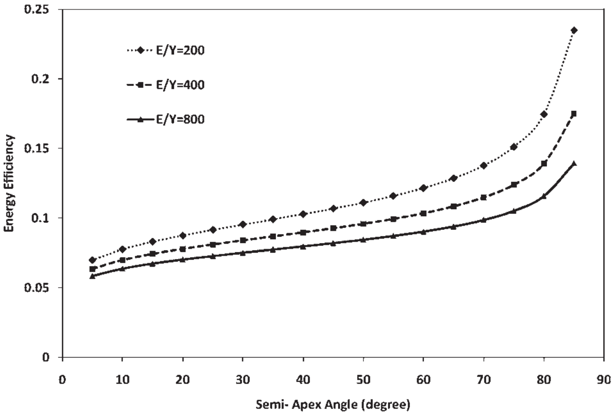
$$U_t = \frac{\pi}{3\ \tan\ \varphi}\left[2Y\ \ln\left(\frac{c}{a}\right) + \frac{2Y}{3}\right]a^3 \tag{14}$$

The above relations show that the energy efficiency depends on the ratio of the plastic zone size to the radius of indentation c/a. Figure 2 shows the variation of the total energy with penetration depth in comparison with the results from indentation experiment on a sandstone (elastic modulus E=5 GPa, Poison ratio v=0·2 and yield strength Y=38 MPa).

As can be seen, equation (14) underestimates the total energy. This is because in the present formulation many factors are not included, such as the energy dissipation by microcracking, material pile-up around the indenter and deformation and closure of intrinsic pores. It is clear, however, that the formulation has integrated the key factors of deformation and has led to a very good agreement with the experimental results.

On the other hand, Johnson[12] derived the following equation for the elastic–plastic boundary

$$\left(\frac{c}{a}\right)^3 = \frac{\frac{1}{2}(E/Y)\cot\varphi + 2(1-2v)}{3(1-v)} \tag{15}$$



3 Variation of energy efficiency with semi-apex angle of indenter

Now the relation between the energy efficiency and the semi-apex angle of the pick can be obtained by substituting equation (15) into equations (13) and (14). Figure 3 shows the variation of the energy efficiency with the semi-apex angle of the indenter for materials with different the ratios of elastic modulus to yield strength. It demonstrates that depending on the geometry of the indenter, only 7–25% of the total energy contributes to chipping and the rest has been dissipated in the formation of the plastic zone. This value is in good agreement with the experimental observations reported in the literature.[5–8] Also It demonstrates that for a material with a higher E or smaller Y, the energy efficiency is lower.

Conclusions

Energy efficiency depends on the size of the plastic zone, i.e. c/a, which in turn depends on geometry of indenter and material properties of specimen. In the case of symmetrical cutting condition or axisymmetric indentation, depending on the semi-apex angle, only 7–25% of the total energy contributes to chipping. For a material with a higher E or smaller Y, the energy efficiency is lower.

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