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Estimating the Peak Indentation Force of the Edge Chipping of Rocks Using Single Point-Attack Pick

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Abstract This article establishes a new model for estimating the peak indentation force of the edge chipping of rocks when using a conical or a pyramidal point-attack pick. The investigation points out that the existing formulation in the literature is based on an inappropriate stress assumption and equilibrium, and hence leads to incorrect cutting force estimations. The new model developed in this study is based on an analysis of the penetration force and energy dissipation using fracture mechanics, similarity of chip geometry, and edge chipping tests on four different rock materials. It is found that the peak indentation force and the depth of cut follow a power law, that the new model can reasonably estimate the experimental measurements, and that it provides useful information for the shape optimization of point-attack picks in mechanical excavation.

Keywords Rock cutting · Point-attack pick · Fracture

1 Introduction

Compared with other methods, mechanical excavation is productive, cost-effective, reliable, and safe. Hence machinery, such as roadheaders, tunnel boring machines, and longwall shearers, has been used extensively in mining and underground excavation engineering (Inyang 2002; Bilgin et al. 2006, 1996; Mishnaevsky Jr 1998; Hood and Alehossein 2000). Significant efforts have been made to understand the mechanism of rock cutting, to enhance cutting efficiency and tool life, to improve work environment and safety, and to extend the capacity of such excavation machines for high strength rocks (Hurt and Evans 1981; Evans 1984; Fowell and Ochei 1984; Hurt and McAndrew 1985; Ranman 1985; Guo et al. 1992; Goktan 1995; Mishnaevsky 1995; Roxborough and Liu 1995; Khair 1996; Goktan 1997; Goktan and Gunes 2005).

A mechanical cutting machine, such as a longwall shearer, cuts rock/coal with an array of picks installed at certain intervals and attack angles on a rotating and moving drum (Hood and Alehossein 2000). The picks, usually made from cemented tungsten carbide or polycrystalline diamond, are often of three types: radial, forward-, and point-attack picks (Hurt and Evans 1981). A radial pick has a wedge-shaped tip, assembled on a shank whose axis is usually perpendicular to the cutting direction. The shank cross section is often rectangular so that the shank does not rotate during cutting to maintain the pick performance. It is generally suitable for cutting soft to medium-hard rock/coal. A forward-attack pick has a wedged tip as well, but its shank is angled backwards from the cutting direction (Hurt and Evans 1981), usually at 45°. A point-attack pick, however, is of a conical shape with a round tip, inserted axisymmetrically into a cylindrical shank. It is, therefore, free to rotate during cutting, making the pick wear more evenly compared with that of the previous two. Point-attack picks have been used in coal mining, but they are more widely used in cutting medium to hard rock nowadays. Actually, unlike a wedge-shaped pick, a point-attack

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pick does not really cut, but works as a sliding indenter to crush, and then breaks the material to produce chips/fragments. Thus, in general, a point-attack pick produces more airborne dust particles regardless of the pick sharpness (Fowell and Ochei 1984; Hurt and McAndrew 1985; Khair 1996; Hood and Alehossein 2000).

The application of a mechanical excavator is often limited by its rotary and thrust force capacity (Hood and Alehossein 2000; Goktan and Gunes 2005; Bilgin et al. 2006; Balci and Bilgin 2007). Though the cutting forces may be measured through full-scale or scaled laboratory cutting tests, the test facilities are costly, and the testing processes are time consuming. Hence, a theoretical or even an empirical model is particularly useful for engineers to estimate the cutting forces, cutterhead torque, and machine power that are required for a particular application, and for the machine manufacturers to optimize the pick geometry to reduce energy consumption and enhance cutting efficiency.

This article is intended to establish a new mechanics model for estimating the pick cutting forces based on the edge chipping of rock materials. The analysis will focus on the application of point-attack picks.

2 Available Models

The cutting by a radial pick can be reasonably simplified into a two dimensional case, and the cutting force can be estimated approximately (Inyang 2002). However, the cutting by a point-attack pick is fundamentally three-dimensional, and is difficult to be simplified. As a result, only a few models have been proposed in the literature (Evans 1984; Roxborough and Liu 1995; Goktan 1997; Goktan and Gunes 2005), such as the Evans's (1984), although their force estimations often deviate considerably from experimental measurements (Roxborough and Liu 1995; Goktan 1997; Bilgin et al. 2006).

As shown in Fig. 1, the Evans' model (1984) assumed that penetration of a point-attack pick produces a radial compressive stress in the material to cut, without friction. When the hoop stress in the material reaches its tensile strength, breakage happens and a symmetric, V-shaped chip segment is produced. The model also assumed that the normal contact pressure between the pick and the material distributed uniformly circumferentially along an imaginary cutting hole, which has significantly ignored the important boundary effect of the edge in the formulation. The pick-material interaction stresses were then determined by taking the equilibrium of the forces on half of the V-shaped chip using a limit analysis (Evans 1984). It was then claimed that the total penetration force was equivalent to the normal force between the material and the pick, leading

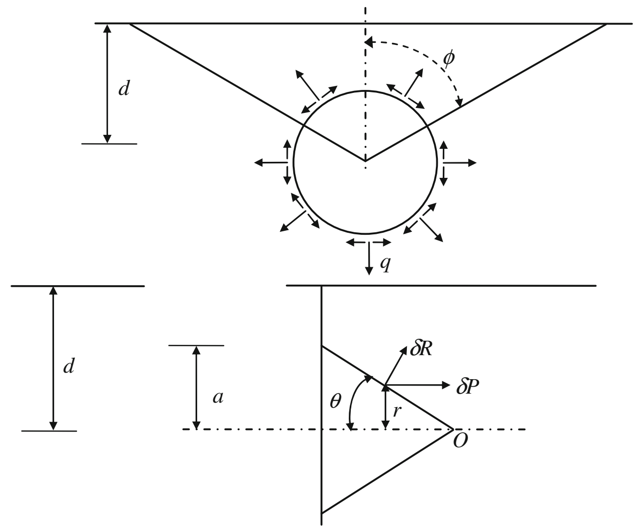

Fig. 1 The schematic diagrams of forces used by Evans 1984

to the following maximum penetration force of the pick to break the material:

$$P_C = \frac{16\pi\sigma_t^2 d^2}{\sigma_c \cos^2\theta} \quad (1)$$

where P_C is the peak cutting force, σ_t and σ_c are the tensile strength and 'unconfined' compressive strength of the material, respectively, d is the depth of cut, and θ is the half conical angle of the point-attack pick. In deriving Eq. 1, however, the stresses on the V-shaped chip do not represent the actual situation, and hence the equation does not reflect the cutting mechanics correctly. Furthermore, the determination of the imaginary cutting hole size is not properly justified (Johnson 1987). As a result, the model could not predict experimental measurements when d varied (Evans 1984).

Roxborough and Liu (1995), Goktan (1997), Goktan and Gunes (2005), and Bilgin et al. (2006) realised that Evans' model could not predict the peak cutting force well. Roxborough and Liu (1995) and Goktan (1997) considered that the inconsistency could be partly due to the effect of friction which Evans had ignored. Based on this, Roxborough and Liu (1995) obtained

$$P_C = \frac{16\pi\sigma_t^2\sigma_c d^2}{\left[2\sigma_t + \sigma_c\cos\theta\left(\frac{1+\tan\Psi}{\tan(\Psi)}\right)\right]^2} \quad (2)$$

but Goktan (1997) brought about

$$P_C = \frac{4\pi\sigma_t d^2 \sin^2(\theta+\Psi)}{\cos(\theta+\Psi)} \quad (3)$$

where Ψ (in degrees) is the friction angle between the pick and the material to cut. Roxborough and Liu (1995) claimed that their model, Eq. 2, could predict well the peak forces in cutting Grindleford Sandstones. Goktan and Gunes (2005) found that Goktan's model, Eq. 3, and Evans' model, Eq. 1, significantly underestimated the peak cutting forces in comparison with the full-scale laboratory experiments. They postulated that this could be due to the symmetrical cutting assumption in these two models. They then provided the following semi-empirical formula for the peak force estimation by curve fitting using their full-scale experimental data:

$$P_C = \frac{12\pi\sigma_t d^2 \sin^2[(90-\alpha)/2+\theta+\Psi]}{\cos[(90-\alpha)/2+\theta+\Psi]} \quad (4)$$

where α is the attack angle of a point-attack pick.

The models presented by Roxborough and Liu (1995), Goktan (1997), and Goktan and Gunes (2005) are basically an extension of the Evans' model by including the effect of pick attack angle and friction between the pick and the material to cut. As pointed out by Bilgin et al. (2006), the peak cutting forces predicted by these models remain very different from the full-scale experiments. These can be caused by the many problems in deriving the Evans' model, as have been discussed above.

Indentation is a very functional way to obtain material properties and peak drill/thrust forces in mechanical excavation of rocks. A significant effort has been devoted to the theoretical and experimental analysis of the indentation of rock materials with either a wedge or a point attack pick (Bilgin et al. 2006, 1996; Cheatham Jr 1958; Copur et al. 2003; Dollinger et al. 1998; Huang et al. 1998; Pang et al. 1989; Paul and Sikarskie 1965; Ranman 1985; Yilmaz et al. 2007). However, it has been found that a conventional indentation formula is not particularly suitable for estimating the peak force of rock cutting. On the other hand, edge chipping for brittle materials (sometimes called edge flaking), as schematically shown in Fig. 2 (Chai and Lawn 2007), has been more widely used to analyse chipping force (Almond and McCormick 1986; McCormick 1992; Quinn et al. 2000; Chai and Lawn 2007; Gogotsi et al. 2007). As indicated in Fig. 2, if the load direction in an edge chipping process is regarded as the cutting direction of the picks, and if the side surface in edge chipping is viewed as the cutting surface, then the edge chipping is similar to a linear rock cutting.

3 Experiment

3.1 Experimental Setup

Geometry similarity of chips is important in the mechanics modeling of rock cutting. To verify such similarity and its relationship with peak forces and depths of cut, a series of edge chipping experiments were conducted on four kinds of sandstone produced in the New South Wales of Australia, Bauhaus, Littlewood, Appin, and Pyrmont. The specimens used for testing were in rectangular blocks with the dimensions of about 217 × 76 × 74 mm, 219 × 118 × 74 mm, 218 × 120 × 71, and 220 × 118 × 73 mm, respectively. Before testing, the specimens were baked in a Labmaster oven at the temperature of 70°C for about 24 h so that each specimen would have the same moisture level. Their mechanical properties are listed in Table 1. To minimise the effect of surface morphology, the specimen surfaces were ground smoothly before testing.

Two types of point-attack picks were used, a conical pick and a pyramidal pick, as shown in Fig. 3. The shape of the pyramidal pick (Zhang and Alexander 2007, 2008) was: half apical angle $\theta = 53°$ and tip radius $r = 1.0$ mm; while that of conical pick was: half conical angle $\theta = 38°$ and tip radius $r = 1.2$ mm.

The chipping tests were conducted on an Instron universal testing machine, Instron 5567, as shown in Fig. 4. The point-attack pick was mounted in the crosshead of a 30 kN load cell. The loading speed was 1 mm/min for all tests. A holding plate was used to fix the rock to avoid any possible rigid body motion of the sample. A digital camera was used to record the pick penetration and sample edge chipping.

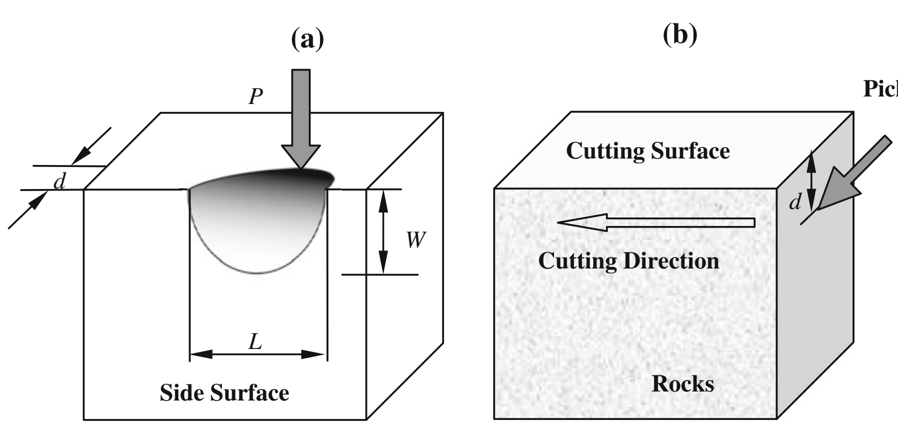

Fig. 2 **a** Edge chipping of brittle materials (Chai and Lawn 2007) and **b** linear rock cutting [side surface of edge chipping in (**a**) is equivalent to the cutting surface of rock cutting illustrated in (**b**)]

Table 1 Material properties of the rock samples after baking

Rock sample name	Bauhaus	Littlewood	Appin	Pyrmout
Water absorption (%)	5.73	5.54	4.07	4.82
Bulk density (kg/m^3)	2,180	2,210	2,280	2,250
Modulus of rupture (MPa)	6.0	N/A	6.2	6.9
Toughness (MPa m$^{1/2}$)	0.70	1.15	0.82	0.91
Apparent porosity (%)	12.49	12.23	9.17	10.83
Compressive strength (MPa)	44.3	53.2	67.3	56.5
Tensile strength (MPa)	3.52	2.9	4.6	4.89
Young's modulus (GPa)	5.0	3.26	2.20	1.30

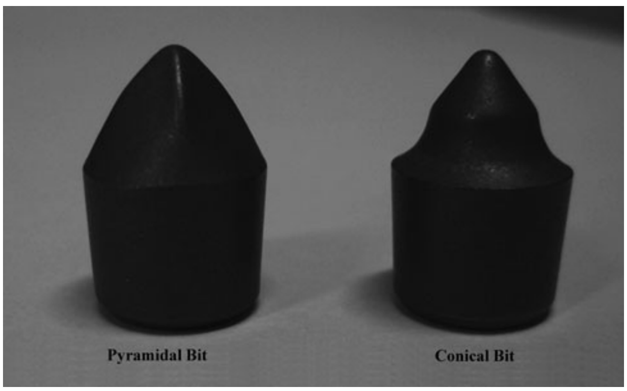

Fig. 3 The pyramidal (*left*) and conical (*right*) picks (Zhang and Alexander 2007, 2008)

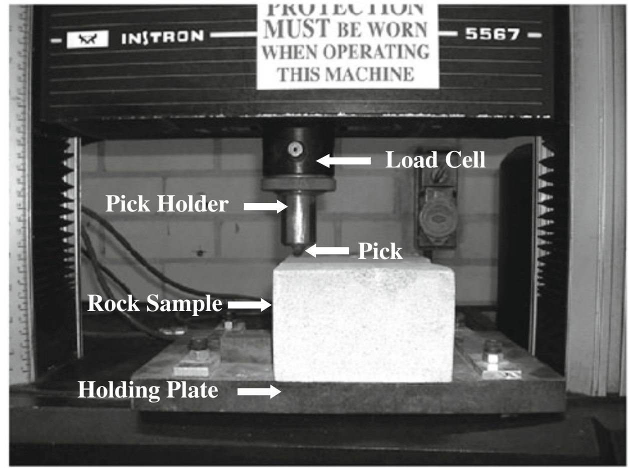

Fig. 4 Experimental setup

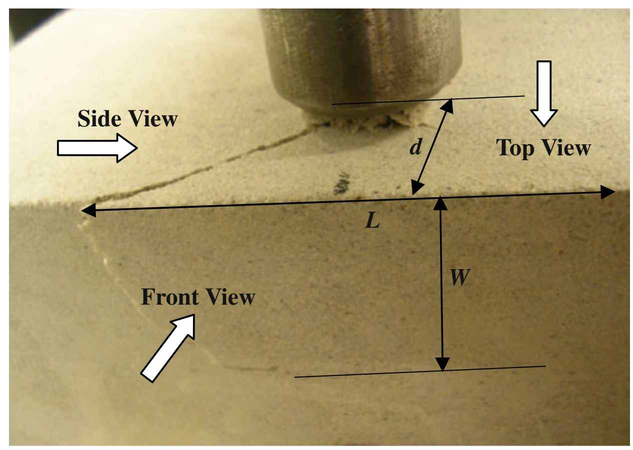

Fig. 5 An edge chipping test with the definition of chip dimensions

In an edge chipping test, the pick was loaded normally to the surface of a specimen at a certain depth of cut *d*—the distance from the indenting point of the pick to the sample edge as shown in Fig. 5. This *d* is equivalent to the depth of cut in linear rock cutting, because, as interpreted previously and indicated in Fig. 2, the edge surface can be viewed as the surface of the rock to be cut. When the pyramidal pick was used, the pyramidal base side was aligned in parallel with the sample edge.

3.2 Observation and Analysis

3.2.1 Chip Geometry

The definition of chip dimensions is shown in Fig. 5. Here, *d* is the depth of cut as defined previously, *L* is the chip length, and *W* is its width. Figure 5 also illustrates three different views for describing the morphologies of a chip in the discussion below, i.e., the top view, the side view, and the front view. Figure 6 shows the top (top row), front (middle row), and side (bottom row) views of three typical chips of the Bahuas samples cut by the pyramidal pick at the depth of cut $d = 8$, 10, and 20 mm, respectively. The shapes of these chips are very similar, and the size of each chip is approximately proportional to the depth of cut *d*. By investigating the chips cut by the same pyramidal pick under various depth of cut (2, 4, 8, 10, 15, 16, 20, 25, and 30 mm) on all the rock samples listed above, a clear geometrical similarity was obtained: the chip length *L* is about four times the depth of cut *d*, and the chip width *W* is about 1.5 times *d*. A few exceptional chips do not exactly follow these proportional factors, which is understandable because the sandstone materials tested were neither isotropic nor homogenous. The above geometry similarity of chips holds in the case of edge chipping by the conical pick, although the scale factors, L/d and W/d, become slightly different.

The above similarity seems to be a general phenomenon in the chipping of a wide class of brittle materials. For example, Almond and McCormick (1986) analyzed the edge flaking of a variety of brittle materials using a Rockwell indenter, and found that there was a linear relationship between the chip dimensions and depth of cut. Many further studies using different indenters (conical,

Fig. 6 Morphology of the chips cut by the pyramidal pick at $d = 8$ mm (*left column*), 10 mm (*middle column*), and 20 mm (*right column*) on the Bauhaus rock

Rockwell, Vickers, and Knoop) concluded that the geometrical similarity of the chips is independent of the brittle materials to cut and of the shapes of the indenters to use, although the proportional factor changes (Almond and McCormick 1986; McCormick 1992; Quinn et al. 2000; Chai and Lawn 2007; Gogotsi et al. 2007). All these indicate that the chip geometry similarity reflects the response of a brittle material to edge chipping, including rocks.

3.2.2 Cutting Force and External Work

To find out the relationship between the peak chipping force and the depth of cut, a series of edge chipping tests with the conical and pyramidal picks were conducted on the four rock materials mentioned above.

Figure 7 shows the cutting force (left) and external work done by the pyramidal pick (right) against the penetration depth within the same Bahuas sample. The depth of cut used was 2, 4, 8, and 60 mm, respectively. At a large enough depth of cut (e.g., $d = 60$ mm), the situation approaches an indentation when the boundary effect of the specimen edge becomes negligible. The results show that when the penetration depth is low, the edge indentation (or cutting) force is close to the indentation force, because the boundary effect from the specimen edge is trivial. During the loading process, the cutting force drops slightly at certain penetration depths, and then rises again with further penetration. This can be regarded as a local chipping, because at this stage, some small fragments/powders, as can be observed clearly during experiments, were generated around the pick. When the cutting force reaches its maximum, it will drop suddenly, corresponding to the completion of an edge chipping. In the process of the local chipping or edge chipping, part of the elastic strain energy stored in the materials is transformed to fracture energy. As shown in Fig. 7, the external works done with different depths of cut do not vary much under the same penetration depth.

Figure 8 shows the cutting force and external work done by the conical pick against the penetration depth in the edge chipping tests, also on the same Bahuas rock sample. The depth of cut used was 8, 10, 15, and 20 mm, respectively. Compared with the pyramidal pick, the cutting force of a conical pick fluctuated more. An observation of the indenting/chipping process in the experiments showed that compared with the pyramidal pick, the conical pick always generates much smaller fragments around the pick, leading to more significant cutting force fluctuation before edge chipping. As a result, the external work done also varies with the depth of cut.

To observe the effect of the inhomogeneity of the rock materials, some edge chipping tests were also conducted on the different Bahuas rock samples. It was found that the variations of the force–penetration curves, energy–penetration curves, chip similarity and peak cutting forces are similar to the previous curves in Fig. 8. This indicates that for the edge chipping tests with the same depth of cut, the micro cracking process can be different due to the inhomogeneity and anisotropy of the sample materials, but the macroscopic behavior/response of the material in edge chipping always happens at the same peak force regardless of the penetration depth.

4 Modeling the Peak Cutting Force

The existing models concluded, as shown in Eqs. 1–4, that the peak cutting force is proportional to the square of the depth of cut. This is not true according to our experimental observations with different depth of cut on all the rock samples mentioned above. Based on the geometric similarity discussed in the previous section, it will be convenient to use an energy method to estimate the peak cutting force with the aid of linear fracture mechanics.

The test results show that the penetration depth before edge chipping is far smaller than the depth of cut. This means that the effect of the edge boundary can be neglected before the occurrence of edge chipping, and that the relationship between the cutting force and depth of cut can be used. According to contact mechanics (Johnson 1987), regardless of the local chipping effect, the relationship between the cutting force and penetration depth of a sharp indenter, including the pyramidal and conical picks, is (Cheatham Jr 1958; Pang et al. 1989)

$$P = \bar{H}h^2 \quad (5)$$

where P is the penetration force, h is the penetration depth, and $\bar{H}$ is the corresponding "hardness" obtained through the indentation test, depending on the mechanical

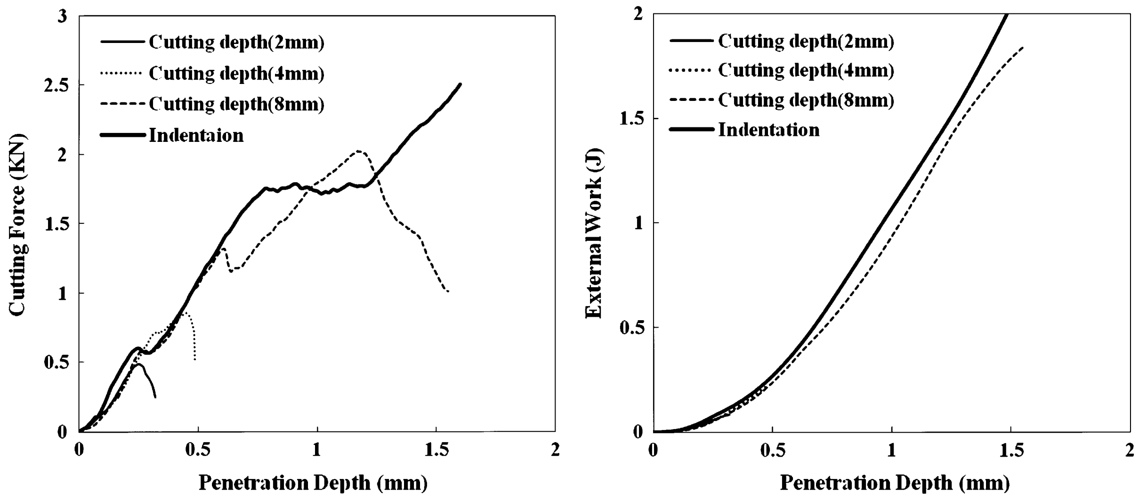

Fig. 7 Cutting forces and external works of the edge chipping tests by the pyramidal pick at $d = 2$, 4, 8 and infinite (indentation) on the Bauhaus rock

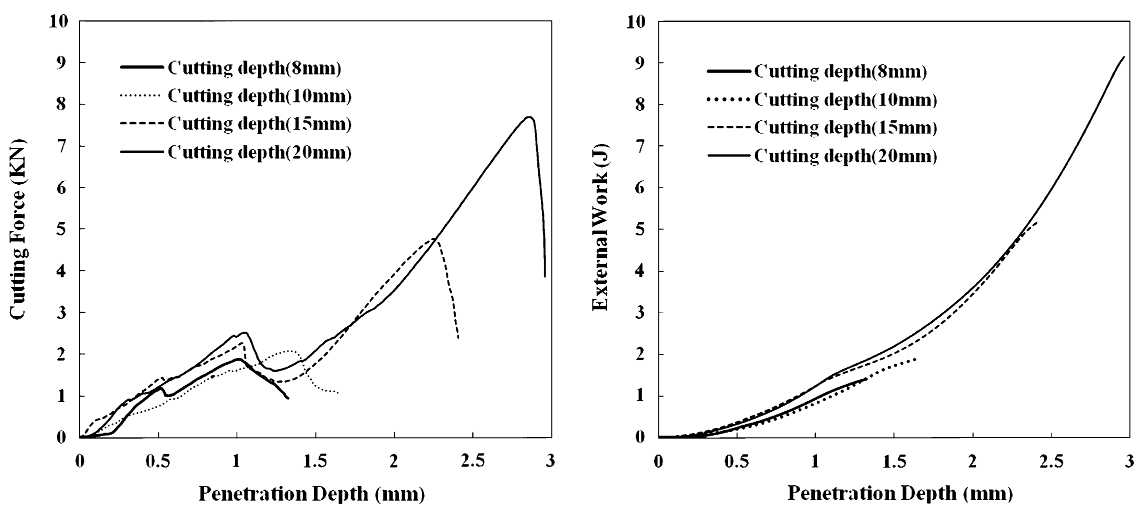

Fig. 8 Cutting forces and external works of the edge chipping tests by the conical pick at $d = 8$, 10, 15, and 20 mm on the Bauhaus rock

properties of the rock material and the pick geometry. For simplicity, here the effect of round tip of the pick is neglected and $\bar{H}$is assumed to be a constant during the penetration process. Integrating Eq. 5 with respect to penetration depth h, we can get the total external work done by the penetration force as

$$W_E = \frac{1}{3}\bar{H}h^3. \tag{6}$$

Therefore, the total external work done by the penetration force just before edge chipping is

$$\bar{W}_E = \frac{1}{3}\bar{H}h_{max}^3 \tag{7}$$

where h_{max} is the maximum penetration depth just before edge chipping.

Since the chips cut by the same pick are geometrically similar as discussed previously, we can conclude the following:

(1) The total area of the new surface generated during edge chipping is proportional to the square of the depth of cut d. This gives rise to

$$A = \gamma d^2 \tag{8}$$

where A is the area of new surface generated during the edge cutting test and $\gamma$is a geometric factor to be

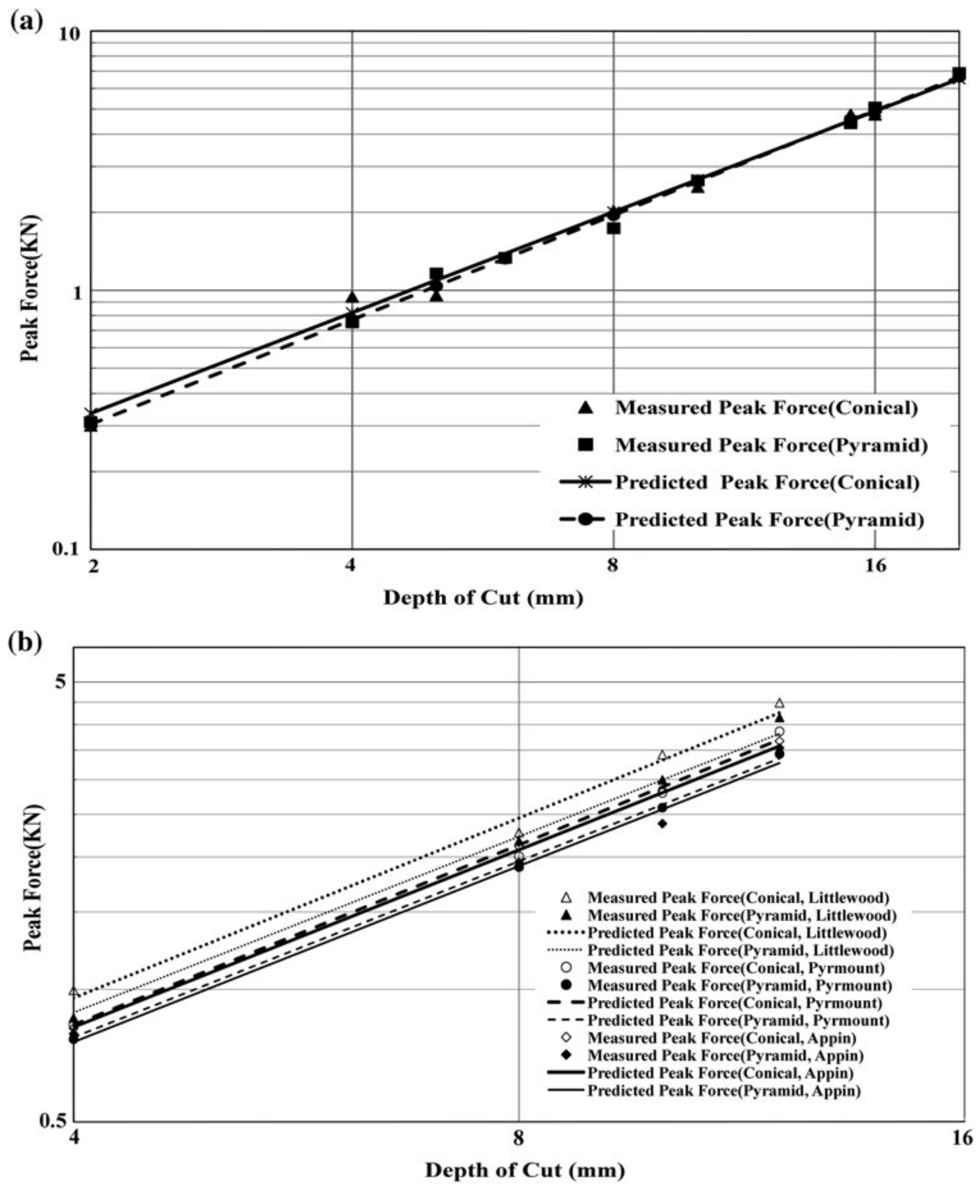

Fig. 9 **a** Comparison of the model predicted peak forces with the experimental measurements (Bauhaus rock). **b** Comparison of the model predicted peak forces with the experimental measurements (Littlewood, Pyrmount, and Appin Rocks)

determined, independent of material properties but dependent on the pick geometry.

(2) The energy needed to generate such new surface, E_s, is a fixed fraction of the total external work done by the penetration force before edge chipping, i.e.,

$$E_s = \kappa \bar{W}_E \tag{9}$$

where κ is a geometric factor of the pick independent of material properties.

According to the Griffin–Irwin theory (Lawn 1993), the total energy needed to generate a new surface is proportional to the area of the new surface, i.e.,

$$E_s = 2G_s A = 2G_s \gamma d^2 \tag{10}$$

where G_s is the strain energy release rate of the material.

With Eqs. 7–10, the maximum penetration depth h_{max} can be obtained as

$$h_{max} = \left(\frac{6G_s\gamma}{\bar{H}\kappa} d^2\right)^{1/3}. \tag{11}$$

Substituting Eq. 11 into Eq. 5, the peak cutting force before edge chipping, P_C, can be expressed as

$$P_C = \Gamma d^{4/3} \tag{12}$$

where

$$\Gamma = (\bar{H})^{1/3}\left(6\frac{\gamma}{\kappa}G_s\right)^{2/3}. \tag{13}$$

Substituting Eq. 11 into Eq. 7 gives rise to the total external work

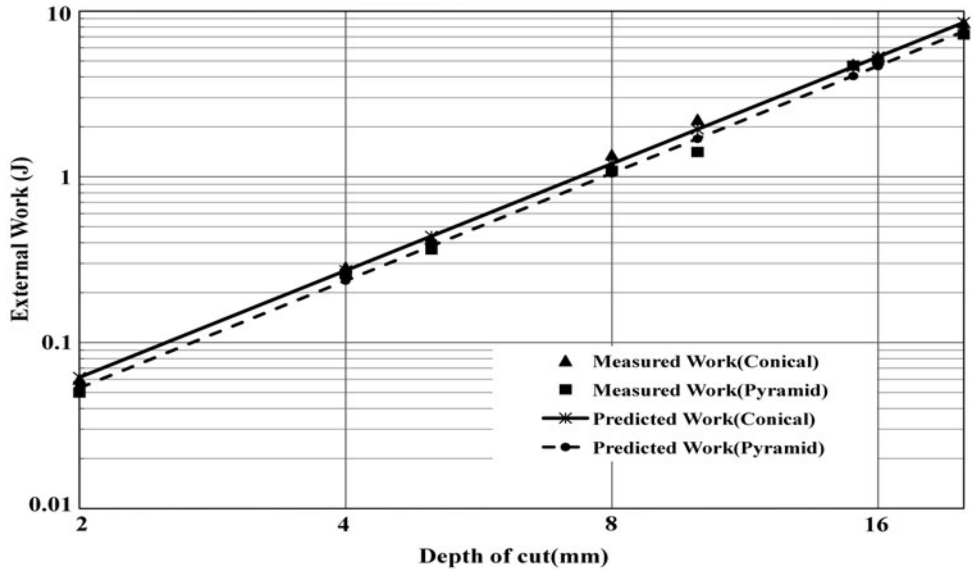

Fig. 10 Comparison of external work (Bauhaus rock)

$$\bar{W}_{\mathrm{E}} = \frac{2G_{\mathrm{s}}\gamma}{\kappa} d^2. \tag{14}$$

5 Model Verification

To examine if the above model can predict the cutting force properly, let us see whether it can reproduce the experimental results discussed in Sect. 2. To this end, we re-write Eq. 5 to a more general form, i.e.,

$$P = \bar{H}h^n \tag{15}$$

where n is dependent on the pick geometry. The peak cutting force can therefore be expressed more generally as

$$P_{\mathrm{C}} = (\bar{H})^{\frac{1}{n+1}} \left(2(n+1)\frac{\gamma}{\kappa}G_{\mathrm{s}}\right)^{\frac{n}{n+1}} (d)^{\frac{2n}{n+1}}. \tag{16}$$

Figure 9a shows the comparison of the model predicted forces with the experimentally measured data in logarithm coordinates, conducted on Bahuas rock with both pyramid and conical picks, while Fig. 9b shows the comparison results conducted on Appin, Littlewood, and Pymount rock samples as well. From these two figures, we can conclude that for both the cases of using the pyramidal and conical picks, n is determined to be about 4/3 (from 1.29 to 1.36) for all rock materials. Hence, our model established, Eq. 12, can accurately estimate the peak cutting forces.

We can also examine the external work done by the cutting force just before chipping. Similarly, we can use a general form of Eq. 7, i.e.,

$$\bar{W}_{\mathrm{E}} = \Lambda d^m \tag{17}$$

where $\bar{W}_{\mathrm{E}}$ is the total external work needed to cut the rock, Λ and m are the coefficient and exponent to be determined. Figure 10 shows the measured and predicted external work needed to cut the rock by both conical and pyramidal picks, demonstrating that the exponent m is indeed around 2, verifying Eq. 7.

6 Energy Efficiency

Now let us investigate the efficiency of the cutting process by examining the percentage of the total energy that is contributed to crack the material. A small percentage means a low cutting efficiency.

According to the material properties listed in Table 1, the strain energy release rate for the Bauhaus rock is about

$$G_{\mathrm{s}} = \frac{K_{\mathrm{IC}}^2}{E} = \frac{(0.70 \times 10^6)^2}{5 \times 10^9} = 98\ (\mathrm{J/m^2}). \tag{18}$$

For the pyramidal pick, Γ estimated from the curve of Fig. 9 is about 0.125 $(\mathrm{KN/mm^{4/3}})$, and the average hardness is about $\bar{H} = 1.1\ (\mathrm{GPa})$. Therefore, using Eq. 13, we get

$$\frac{\gamma}{\kappa} = 71.66. \tag{19}$$

Moreover, the geometric factor γ is found to be between 5 and 10. Therefore, Eq. 18 gives $\kappa = 7 - 14\%$. This means that in average, only about 10% of the total external work contributes to the generation of new chipping surfaces while most of the external work is dissipated in producing the crushing zone.

7 Conclusions

This study has established a new mechanics model for predicting rock cutting forces. The model has been verified by a series of tests using the conical and pyramidal point-attack picks on four rock materials. The main conclusions are as follows:

(i) The cutting peak force and the depth of cut have a power law relationship with the component equal to 4/3, as shown in Eq. 12.
(ii) The total external work done by the cutting force is proportional to the square of the depth of cut.
(iii) Using a point-attack pick, only about 10% of the total external work contributes to the generation of new surfaces.

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