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Principles of diamond tool technology for sawing rock

B. Brook*

6 Erin Court, Port Erin, Isle of Man IM9 6LN, British Isles, UK

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Abstract

In a rock sawing operation, a single diamond particle acting as a sliding indenter expends energy by generating compression in the rock in the form of a 'stress epicentre' through the action of confined crushing: this compression causes the rock fracture mechanism. It is not a cutting operation per se—indeed sharp diamond particles can be a liability. The sawing requirement is for a high strength, high heat resistance indentor, with a potential for displacement that is compatible with that of the rock. Currently used tests for rock strength do not indicate energy consumption, but the Shore and Brinell hardness tests are relevant. However, the consumed energy is predictable from a new index of rock strength, called Brook hardness, which has been specifically developed for sliding diamond indenters. The 'stress epicentre' is located with reference to the diamond indenter through a force vector which is stable for all circular sawing velocities, but it changes with frame sawing and drilling because they operate at about a tenth of the sawing velocity. The 'stress epicentre' is at the location of the crushed, compacted material under the indenter. Changes in the position of the stress epicentre can increase energy efficiency by as much as 100% and reduce the generation of vertical force by as much as 70%. Drilling tests using feed/revolution as the measure of penetration are used to simulate the variable velocity of frame saws by reducing the revolutions/minute. These tests reveal a previously unrecorded sawing mechanism that can improve the use of frame saws because strong granite can now be frame sawn with diamond. This improved potential should also apply to drill bits if they use feed per revolution as the means of penetration, instead of a static bit load. By measuring diamond by volume rather than by weight, and considering alternative options, accurate tool control can now be achieved, with every aspect being predictable. Optimisation of rock sawing operations has shown that performance can be increased by 100–200% with tools removing as much as 30 tonnes in saw cuts per carat of diamond consumed. Because some rock mechanics terms used in the paper may have different meanings in the rock sawing context, a glossary of terms with further explanations is included at the end of the paper.

1. Introduction

1.1. Background

The World Stone Industry Report for 1995 [1] estimated world production of dimension stone to be 37.8 million tonnes. Primary sawing of the stone into thin slabs is usually carried out by frame saws with linear blades and a reciprocating motion, driven by a crank with a 500 mm stroke. About 30% of this total dimension stone production is granite and other hard rock that cannot be frame sawn with diamond.

Fig. 1 shows the type of machine used and Fig. 2 shows the result of the sawing process that may have taken 72 h to complete. Loose abrasive is used in this sawing process which is fully automated, operating 24 h a day; it is a slow, dirty process and yields large quantities of waste heavily polluted with metal oxides, but it is relatively cheap. The machines are large, with an overall length of 16 m and a height and width of 6 m having a total weight in excess of 50 tonnes and requiring complex foundations.

Fig. 3 shows diamond-tipped frame saw blades cutting a block of sandstone. The maximum slab size was $3 \times 1.5\,m^2$ and 2.5 h are required to complete the sawing operation. The diamond segments in this picture are surface set diamond with 12 stones per segment (24SPC), equally spaced at 150 mm centres; this puts 10 carats of diamond in contact with each blade and was only successful because of the relatively slow velocity of the machine, 305 mm stroke $\times$ 85 rpm, or 1.36 m/s crank velocity which is half that of a standard frame saw.

In 1978, five identical machines converted 15,000 tonnes of block into 100,000 m^2 of slab in 2000 h for a net diamond loss of 45 carats; this loss was due to segment wear allowing the diamond to fall

*Tel.: +44-1624-834085.

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Fig. 1. Loose abrasive frame saw.

Fig. 2. Frame sawn granite slabs.

out. There was virtually no wear on the diamond particles, even though the majority of the segments had been re-cycled over a 3 yr period. Machine weight was 8 tonnes with simple foundations, making a considerable difference in the initial capital cost.

Fig. 4 shows a typical mono diamond blade linear saw. This type of saw is versatile because it can accept the largest of normal block sizes or irregular shaped lumps. They can be programmed to operate unattended for long periods sawing most types of rock, but they have not been successful with granite.

Fig. 5 shows a large-diameter circular saw cutting granite. Care has to be taken with these as relatively low performance can generate sufficient stress to deviate the blade; not only will the saw cut then be useless, but the blade will be damaged and may have to be removed for re-tensioning. Performance on granite should be about

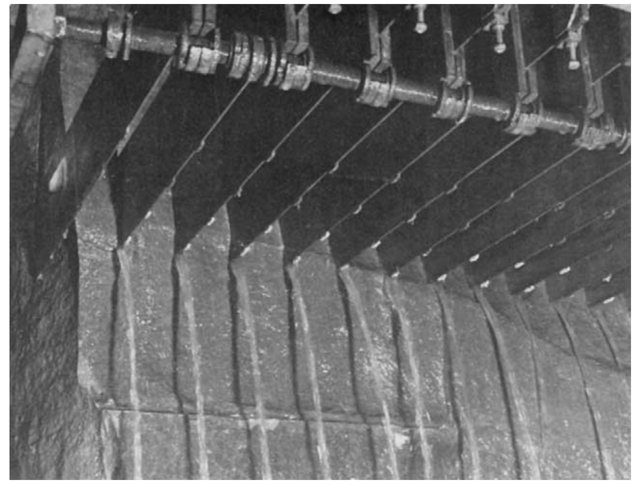


Fig. 3. Diamond frame saw blades.

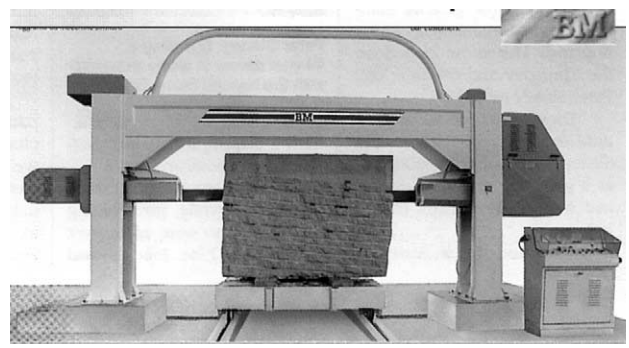


Fig. 4. Diamond mono blade saw

Fig. 5. Circular saw cutting granite.

1000 cm^2/min but this is never achieved—the reasons will be explained later. Maximum performance on easier cut materials should be 3000 cm^2/min, again, this is seldom achieved as a 12 mm cut is removing about 10 kg of rock every minute, and the difficulty is ensuring sufficient water is introduced into the cut to dilute the slurry.

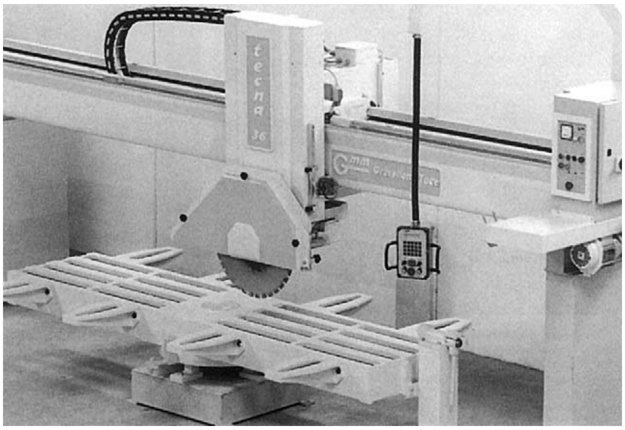


Fig. 6. Bridge saw.

Fig. 6 illustrates a small circular saw for secondary cutting, normally referred to as a Bridge saw. Six bridge saws accompanied the five frame saws as shown in Fig. 3 with blade diameters from 500 to 1000 mm; the maximum depth of cut could be taken in one pass by all machines, with a performance of 3000 cm^2/min and an average rate of wear of 0.003 mm/m^2 sawn. This high performance was achieved by reducing the recommended velocity from 50 to 30 m/s. The low rate of wear was achieved by using maximum strength synthetic diamond instead of a friable type normally recommended for rock with a Shore hardness of 32. A 360 m diameter $\times$ 50 mm wide milling wheel was frequently used on all machines, reducing the velocity on some quite considerably, yet it had little effect on performance which was a removal of 1000 cm^3/min, yielding a tool life that was frequently 9 months of almost constant use.

The potential output of this unit was 25,000 tonnes per year. In an attempt to encourage further sales, 40% was being sold at cost; yet after the deduction of depreciation, gross profit was 39% of sales value. It showed what can be achieved by altering the parameters.

The current design for frame saw blades, that introduces a slight downward bow when fully tensioned in the machine, is the design for sawing wood. Rock has an opposite requirement, necessitating the use of low diamond concentration segments which have a short operational life, 3 months compared to 3 yr, the blades shown in Fig. 3 being non-standard.

2. Current diamond tool technology

2.1. Diamond quality

The quality of natural diamond is usually governed by its source, and can be enhanced by visual expert selection to flawless stones of almost spherical shape for further enhancement so that they can be used for surface set drill bits. The majority of natural diamond mesh sizes used for sawing will be based on the residue of untreated diamond boart that is then crushed and screened to specified mesh sizes. Initially, these sharp particles will yield high performance for low energy input but, as they wear, loads increase and diamond particles have to be discarded through controlled bond metal erosion—otherwise the whole tool will have to be scrapped through inability to support the required loads.

This has led to the mistaken belief that a sharp point is the key to efficiency. A point-like particle has diminished force capability in comparison with a sphere; however, it requires very little loss in volume to increase this loading dramatically. A spherical particle will last much longer without increasing the energy requirement, similar to the button cutters on tunnel boring machines. Indeed, spherical stones are selected for drill bits based on years of experience to yield a long life. Sawing and drilling use the same principles but at a different velocity: the lower drilling velocity introduces a simple change to the mechanism of energy transfer which can have a profound effect on what can be achieved. The optimal specification for a drill bit cannot be used for high velocity sawing of the same type of rock.

High quality synthetic diamond has the regular shape of a cube-octahedron, which can be considered to be a sphere with facets. All such regular shapes that can be contained by a sphere maintain a similar potential of mm^3/mm^2 at the mid-position, as that of the sphere.

Diamond manufacturers have introduced 8 grades of friability in their popular range to ensure that sharp points can be generated by soft rock. The MBS range by General Electric, starting at its weakest is 710, MBS, 720, 730, 740, 750, 760, and MSD. The SDA range by DeBeers duplicates the same variation with 25+, 45+, 55+, 65+, 75+, 85+ 100+, and 100S.

2.2. Control of diamond particle size

Diamond mesh sizes are available in wide or narrow ranges where the wide range spans two narrow ranges. As an example, 40/50 US mesh is a wide range with 1850 particles per carat, controlled by FEPA D427. 99.9% must pass through a sieve of 0.600 mm, 8% can be retained on the upper sieve of 0.455 mm with 90% retained on the lower sieve of 0.302 mm, with 8% passing through; only 2% can pass 0.213 mm.

80/100 US mesh is a narrow range with 17,058 particles per carat, controlled by FEPA D 181. 99.9% must pass through a sieve of 0.271 mm, 10% can be retained on the upper sieve of 0.197 mm with 87% retained on the lower sieve of 0.151 mm, with 10% passing through; only 2% can pass 0.107 mm.

This explains the wide variation in diamond particle sizes that has led to the current belief that accurate tool control cannot be achieved, but volumetric displacement yields a proportional force or pressure and, for most purposes, this complexity can be ignored with the introduction of average diamond particle diameter (ADPD) based on volume, which will be explained later.

2.3. Lack of accurate data

There is no lack of accurate data for the manufacture of diamond impregnated tools; the problems arise when attempts are made to optimise their performance for sawing rock that can vary in hardness from 20 to 120 shore. The German Industry Standard DIN 8589 [2] describes diamond impregnated tools as 'cutting with a geometrically indeterminate edge', with random exposure of diamond particles with FEPA specification. This appears to be justified, but it is actually a deterrent to progress, an industry standard usually explains the methods of achieving enhanced performance. One that explains that it cannot be achieved has no purpose.

Current recommendations suggest 50 m/s velocity for circular sawing of easily cut rock, then 30 m/s and step cutting for sawing hard granite. This would only be applicable if one were attempting to saw both types of rock with the same tool. It is obviously not the best choice, yet toolmakers persist in trying to cut granite with a Shore hardness of 80 to 100 with a diamond mesh size of 40/50 US mesh, yielding inadequate performance. Profit is essential for both the toolmaker and the user; if the user cannot make a reasonable profit, there is no future for either.

Sawing test analyses are vital for progress, but they are dependent on specifying the optimal potential of a tool—which cannot yet be described. Progress is currently being attempted but from experience based on a principle that is flawed. The process of sawing rock with diamond particles is not a cutting operation: it is confined crushing operations where the requirements are opposite.

3. Principles and mechanisms

3.1. Hypothesis

Volumetric displacement is the mechanism which generates pressure and this can be considered an alternative for hardness. Shore and Brinell hardness become specific when the load per area (kg/mm^2) also specifies the volume displaced (mm^3/mm^2) that generated the load. If the load (kg) is divided by the volume (mm^3), it indicates a figure that relates to a load (kg) generated by indenting 1 mm^3 in 1 mm^2; all other indentations on the same material will be proportional to this figure.

This rock hardness, termed here the 'Brook hardness' can be related to the energy requirement of diamond particles sawing rock, where 1 carat of diamond is shown to have a volumetric displacement of 57 mm^3 which can be related to every diamond mesh size by the number of particles per carat and the generation of an ADPD—where pressure is the fracture mechanism for rock chips whose size is dependent upon the diameter of the indenter and the depth of indentation. The Shore hardness number is also the optimal diamond mesh size, i.e. 88 shore = 80/100 US mesh. The displacement of the ADPD at mid-position, which is the point of maximum excavation, is also the displacement achieved by Brinell for equal hardness.

The 'stress epicentre' generated by indentation will have variable pressure from base to tip. Energy transfer from tip to chip is inefficient and the actual energy requirement is for overcoming the resistance of the rock to shear stress. The pressure generation will vary with different diameters of indenter but, to some degree, this variability will be compensated by variable penetration of the epicentre to achieve fracture. The energy input is not a problem: the problem is the generation of vertical force, F_z, a by-product of the pressure, because it can cause tool deviation on hard rock.

The position of the epicentre is controlled by the force vector which is stable for high velocity sawing but, at low velocity, the angle changes and the point of contact becomes closer to the high pressure region, thus making the operation more efficient by reducing the energy input with reduced pressure. This also has the benefit of reducing the generation of the vertical force, F_z.

The introduction of ADPD enables all excavation dimensions to be calculated allowing tool control and test analysis to achieve high accuracy.

3.2. Pressure as the fracture mechanism for rock

A common method of inducing rock to fracture is to drill a hole and apply pressure through explosives or a wedge with energy input from a hammer. Fracture can also occur from direct impact by a hammer or from the constant force applied by a breaker bar on a hydraulic guillotine machine. The resistance of the rock is its shear strength; when the force is greater than the resistance, fracture occurs. Fig. 7 shows the conventional shape of a breaker bar for a guillotine. The curved fracture shown is usually associated with rock anisotropy. The radiused contact illustrated in Fig. 8 was used on a machine designed by the author which had 100% contact on four edges of a sawn strip of sandstone. This produced an ideal fracture through the microstructure but, after each cut it, was noticed that there was a slender 'beard' of dense, fine grain powder, highly compacted and firmly

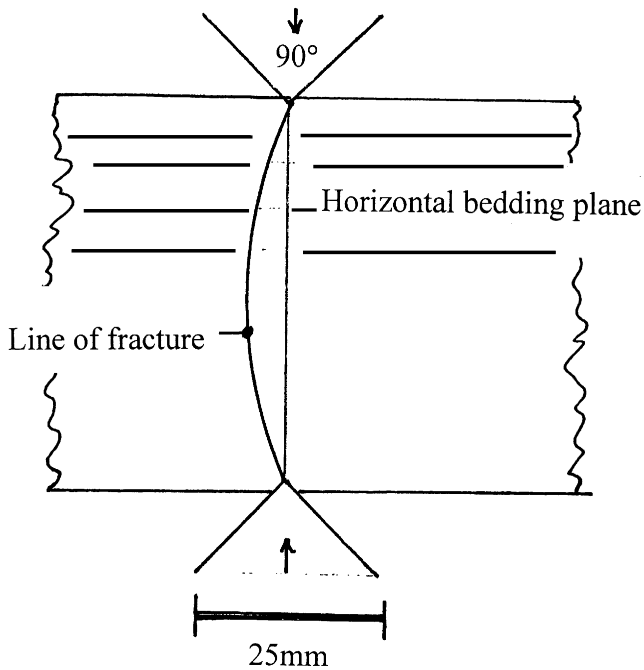


Fig. 7. Cutter bar variations for guillotine machines.

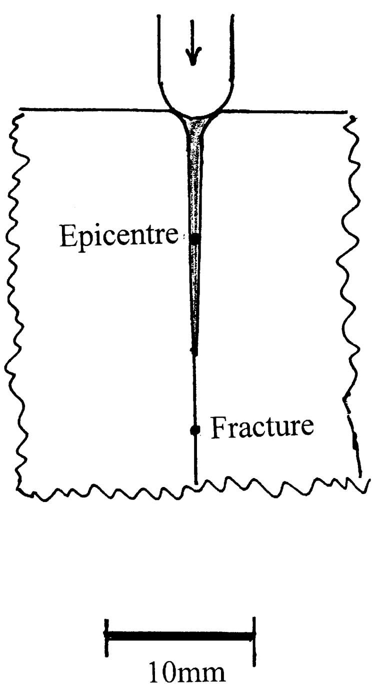


Fig. 8. Cutter bar variations for guillotine machines.

attached to the breaker bar with a length of 15–20 mm. It was assumed that this stress epicentre was the actual fracture mechanism where force achieves indentation, pressure is generated and distributed through the epicentre with a suitable action for fracture. It was also assumed that pressure would diminish from base to tip, and that direct impact with a hammer would reproduce almost identical results.

To solve the mechanism of pressure generation by volumetric displacement, the search eventually turned to the Shore hardness test which duplicates the hammer blow to reveal a number that is related to pressure that initially reveals little, but after analysis provides the required information. Shore hardness can be converted to Brinell hardness accurately for the whole range of rock hardness. The conversion allows accurate dimensions to be introduced so that displaced volume can be measured and related proportionally to other sizes of indenter.

3.3. Rock fracture—chip size ratio

When dressing a piece of granite with a hammer and punch, it was noticed that all the chips were circular in shape with diameters from 100 to 20 mm, with complete feather edges. Checking the thickness with a micrometer revealed that the diameter was four times greater than the thickness with a remarkable consistency. It was considered that each chip was a manifestation of its own tensile strength, and the energy required to detach it would be based on the surface area of the new fracture and the shear strength of the rock. It was also considered that this aspect ratio would be maintained even for micron sizes and a fracture model was developed based on the feed depth (F) of a circular saw. The occurrence of a fracture is cyclical with a length of F, the volume of one chip is F^3 and the area of the new fracture is $6F^2$. This formula is used later for sawing test analysis to compare maximum and minimum feed depths. The energy requirement for a single diamond particle remains constant irrespective of feed depth; the chip size is the ultimate guide to efficiency.

A good blacksmith can produce a sharp point on a punch, but even the best temper is easily broken on granite. The sharp point will only generate small chips because penetration generates little pressure; a worn point with a radius of 1.5 mm is efficient and capable of generating large chips, but point wear can be rapid and, by the time the point has a 3.0 mm radius, the force of the hammer blow has had to be increased. The angle of the punch can be altered to affect chip size, but the fracture mechanism remains constant: indentation generates pressure to initiate a fracture, the taper of the shank following through removes the chip with virtually no additional energy input. In many instances, chips appear to be blasted loose with almost explosive force to travel considerable distance, confirming that pressure was involved.

3.4. Sawing tests—conventional analysis

In 1989, at the author's request, G E Superabrasives, Frankfurt, carried out a series of circular sawing tests in a downcutting mode in their laboratory to check the

Table 1
Sawing test data

Horizontal feed		Depth of cut				
		5 mm	10 mm	15 mm	20 mm	25 mm
1.0 m/min	Perf. power F_z	Test	1. 100 cm^2/min 5.2 kW 2675 N			2. 250 cm^2/min 8.8 kW 3350 N
1.5 m/min	Perf. power F_z					3. 375 cm^2/min 9.4 kW 3175 N
2.0 m/min	Perf. power F_z	4. 100 cm^2/min 4.0 kW 1600 N	5. 200 cm^2/min 5.7 kW 2027 N	6. 300 cm^2/min 7.4 kW 2420 N	7. 400 cm^2/min 8.7 kW 2600 N	8. 500 cm^2/min 9.95 kW 2500 N
3.0 m/min	Perf. power F_z		9. 300 cm^2/min 6.3 kW 1970 N			10. 750 cm^2/min 10.2 kW 1540 N
4.0 m/min	Perf. power F_z	11. 200 cm^2/min 4.5 kW 1340 N	12. 400 cm^2/min 6.5 kW 1340 N	13. 600 cm^2/min 8.5 kW 1340 N		

Table 2
Conventional sawing test analysis

Test	(kW)	Volume removed (mm^3/s)	Load (N)	Efficiency achieved (mm^3/W)	Average feed mm 4.5 mm wide	Pressure generated (N/mm^2)
1	5.2	750	160.0	0.1442	0.00513	6933
4	4.0	750	123.1	0.1875	0.00513	5333
2	8.8	1875	270.8	0.2131	0.01282	4693
5	5.7	1500	175.4	0.2632	0.01026	3800
3	9.4	2812.5	289.2	0.2992	0.01923	3342
6	7.4	2250	227.7	0.3041	0.01538	3289
11	4.5	1500	138.6	0.3333	0.01026	3000
7	8.7	3000	267.7	0.3448	0.02051	2900
9	6.3	2250	193.8	0.3571	0.01538	2800
8	9.95	3750	306.1	0.3769	0.02564	2653
12	6.5	3000	200.0	0.4615	0.02051	2167
13	8.5	4500	261.5	0.5294	0.03077	1889
10	10.2	5625	313.8	0.5547	0.03486	1813

effects of various depths of cut combined with various rates of horizontal feed in the pursuit of optimum performance. Table 1 lists a summary of the results.

Saw blade

650 mm diameter × 4.5 mm wide with 36 segments 40 mm long,

30 concentration = 1.32 carats per cc or 7.5% of segment volume,

40/50 US mesh = 1850 particles per carat of MBS 70 quality (friable),

955 rpm = 32.5 m/s velocity.

Material

Orienta granite, Shore hardness = 88.0, UCS = 148 MPa,

group III difficult to saw,

conversion to Brinell = 88.0 × 7.033 = 618.9 kg/mm^2 (40.95 times UCS).

Methods of analysis

kW × 1000 = watts,

Watts divided by 32.5 m/s velocity = torque load (N),

Total volume removed in 1 s divided by total watts = efficiency mm^3/W,

Feed per minute × depth of cut divided by (32,500 mm × 60) = (average feed) (mm),

Average feed (mm) × 4.5 mm tool width = excavated area (mm^2),

Torque load (N) divided by excavated area (mm^2) = pressure generated (N/mm^2),

1000 mm^3/divided by pressure (N/mm^2) = Efficiency mm^3/W,

The tests are listed in order of increasing efficiency (mm^3/W) in Table 2.

3.5. Variations in diamond description

100 diamond concentration = 4.4 carats per cm^3 of segment volume, but it also represents 25% of the segment volume; in future, diamond content will be

expressed as a percentage of the segment volume. As 4.4 carats represent 25% of 1000 mm^3, the volume of 1 carat of diamond is about 57 mm^3. When the number of particles per carat (PPC) is specified, the ADPD can be calculated. As an example, 40/50 US mesh has 1850 PPC, the average volume (V^1) for 1 particle = 0.0308 mm^3, the cube root of $V^1 = 0.3135$ mm ADPD.

3.6. Random diamond protrusion

The distribution of diamond particles within the segment matrix is random, but it must also be even. The maximum protrusion cannot exceed $\frac{1}{2}$ADPD or the particle will fall out, and the minimum protrusion will be close to zero. Thus, the average maximum protrusion should not exceed $\frac{1}{4}$ADPD. This is applicable in all directions and is given the designation 'X' for analysis and tool control.

3.7. Dimensions of multiple point contact

Optimum feed depth sawing hard abrasive granite is $\frac{1}{6}$th ADPD which is designated as F^1: this allows room for chip movement without endangering the stability of the diamond. A circular saw generates a diminishing feed and F^1 taken at the point of entry will diminish to zero at the point of exit—therefore, all calculations are made at the point of the average feed, and F^1 will have generated 4 track paths (X_g) in the width of 1ADPD. At the same time, the contact layer, comprising exposed and unexposed diamond particles, will also have a depth of $\frac{1}{4}$ADPD. Therefore, the sectional area of 1 track is X^2. Indentation of a diamond particle generates a radius of indentation (X_c) and the track or groove width (X_g), $X_c \times X_g = X^2$. The dimensions of X_c are infinitely variable, whilst it is increasing, the number of points in contact will also be increasing and reducing the width of X_g, maintaining $X_c \times X_g = X^2$ (constant) as the area of indentation for 1 diamond. The sectional area of one track is also constant as X^2 is dependent upon the following data.

3.8. Pressure generation by sliding indentation

Within the test analysis is a denominator of 660 N/mm^2 common to every test. For variable pressure, there has to be a maximum and a minimum and a constant formula for the variation. Dividing 1000 mm^3 by 660 N/mm^2 gives 1.515 mm^3/W as the maximum efficiency, with a designation of 1.0 E. This figure divided by the mm^3/W achieved by all the tests indicates a different value for E, 660 N/mm^2 × E = pressure.

$X^2 \times 660$ N/mm^2 = indentation load (N) for 1 diamond particle (constant).

Fig. 9 is the mechanism of a single diamond sliding indenter; the common denominator is now called 'Brook hardness' as will be explained. E is a mechanical function of indentation, which can be calculated, but initially when all that is known is E and ADPD, F and X_c can be calculated as explained in Fig. 10.

The force vector is not active at high velocity, but at low velocity the chip engages the epicentre closer to the base and receives higher pressure to break out the chip. As the fracture resistance has not changed, the energy input is reduced, in turn this also reduces the generation of vertical force F_z which is based on pressure—see Table 3.

3.9. Tool control

With the dimensions of multiple point contact, tool control is a simple calculation based on one track, as all other tracks are identical.

$$\frac{\text{total segment length } \times X^2 \times \text{diamond \%} \;=\; \text{diamond particles in 1 track of } 360^\circ}{V^1}$$

diamond particles in 1 track × F^1 = Feed per revolution (90° contact).

To accommodate the diminishing feed of a circular saw, calculate the contact angle from the blade diameter and the depth of the cut; divide feed per revolution by the sine of the contact angle to reveal the optimum horizontal feed per revolution.

At some point, the total number of points in contact is required.

$$\frac{\text{total segment length} \times \text{tool width} \times X \times \text{diamond \%} \;=\; \text{points in contact for } 1^\circ}{V^1 \times 360^\circ}.$$

Given the contact angle, the total number of points in contact is a direct calculation. Table 4 lists optimum performance for each depth of cut and the number of points in contact, which can be compared with the actual achievements of the closest horizontal feed.

3.10. Sawing test analysis based on brook hardness

Methods of analysis

$E \times 660$ N/mm^2 = pressure,

F and X_c are calculated from E and ADPD,

X^2 divided by $X_c = X_g$,

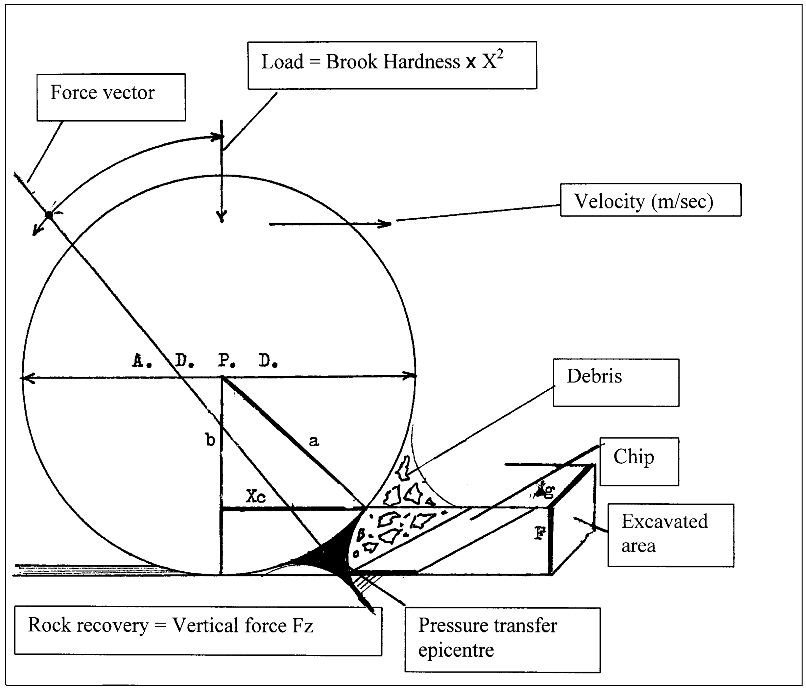
Average feed divided by point feed F = points in 1 track,

4.5 mm tool width divided by X_g = total tracks,

Total tracks × points in 1 track = total points,

Total load (N) divided by ($X^2 \times 660$ N/mm^2) = total points,

$X_g \times F \times 32,500$ mm × total points = calculated volume removed in 1 s.



X = ¼ ADPD for tool control

Xc = Radius of indentation

Xg = Track or groove width

F = Feed depth or point feed

$\frac{Xc}{F}$ = 'E' pressure generator

Xc x Xg = X^2 Indented area

Xg x F x E = X^2Area of one track

Brook Hardness = 1/10th of Brinell

Brook Hardness x E = Pressure (N/mm^2)

Fig. 9. The mechanism of a single diamond sliding indenter.

3.11. Comparison of chip size with area of new fracture

Tables 5 and 6 shows that, for maximum and minimum feed, the indentation load was identical to remove a volume of $X^2 \times F$, where maximum is 13 times greater than the minimum, but equality is maintained through the surface area of new fracture.

4. Rock strength

4.1. Description

The tensile strength of rock governs chip size; the shear strength of rock governs the net energy needed to produce a single chip based on the surface area of a new fracture on the chip. The unconfined crushing strength is not directly relevant. The Shore hardness number is only of value once converted to Brinell hardness as kg/mm^2, which is not a fixed value. Hardness is the ability of a material to accept volumetric displacement—which results in the generation of pressure. Shore and Brinell use the same indentation load on the same diameter of indenter to test everything; what we want to know is what will be the load to indent a sphere to its mid-position, to achieve maximum excavation potential, and what is the optimum diameter of the indenter? The excavation potential of one carat of diamond is identical irrespective of the mesh size, because there is an indentation of 50% of 57 mm^3 in each case.

4.2. The potential and proportionality of spheres

The maximum indentation potential for a sphere is at its mid-position and is measured by dividing half of its total volume by the flat area of the mid-position to reveal the potential in mm^3/mm^2. A 10 mm diameter ball is used as an example

$(10\,\text{mm}^3 \times 0.5236)/2 = 261.8\,\text{mm}^3$ volume,

$5\,\text{mm}^2 \times \pi = 78.54\,\text{mm}^2$ area,

Volume/area = 3.333 mm^3/mm^2 maximum potential at mid-position.

Example of known facts

40/50 US mesh ADPD = 0.3135
$F^1 = 1/6^{th}$ ADPD = 0.05225
$a'' = 0.1567$
$b'' = 0.1045$
$\sqrt[2]{a''^2 - b''^2} = Xc = 0.1168$
$Xc/F' = 2.236 =$ 'E'

Example of formulae when given 'E' and ADPD

'E'	2.236
ADPD	0.3135 mm
$a'' = \frac{ADPD}{2}$	0.1567 mm
$\frac{1}{E}$ inv.tan. = A'	24.09°
$A'' = A' \times 2$	48.19°
$b'' = a'' \times \cos A''$	0.1045 mm
$F' = a'' - b''$	0.05225 mm
$b' = \frac{a'}{\sin A'}$	0.1280 mm
$Xc = b' \times \cos A'$	0.1168 mm
$\frac{Xc}{F'} =$ 'E'	2.236 'E'

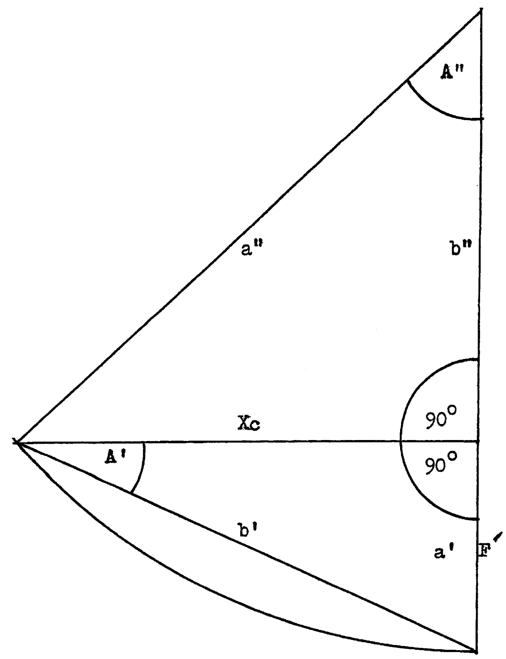


Fig. 10. Calculating indentation dimensions when given E and ADPD.

Table 3
Saw test analysis[a]—pressure as the source of vertical force, F_z

Test	Points in contact	Pressure (N/mm^2)	F_z (N)	F_z (N) 1 point	F_z Ratio to point load
1	39.47	6933	2675	67.78	16.72
4	30.36	5333	1600	52.70	13.00
2	66.79	4693	3350	50.16	12.37
5	43.26	3800	2027	46.85	11.56
3	71.34	3342	3175	44.50	10.98
6	56.16	3289	2420	43.09	10.63
11	34.15	3000	1340	39.23	9.68
7	66.03	2900	2600	39.37	9.71
9	47.81	2800	1970	41.20	10.16
8	75.52	2653	2500	33.10	8.17
12	49.33	2167	1340	27.16	6.70
13	64.51	1889	1340	20.77	5.12
10	77.41	1813	1540	19.89	4.91

[a] The number of significant figures is that used in the calculations and is not intended to indicate experimental accuracy.

All other spheres are proportional to this by the ratio of their diameter; the maximum potential of a 1 mm sphere is 0.3333 mm^3/mm^2.

To measure the displaced volume for any depth of indentation, the flat radius of permanent deformation is needed, plus the theoretical depth of indentation that this would produce.

The radius divided by the depth of indentation = E.

The maximum potential (mm^3/mm^2) divided by E^2 = displacement achieved mm^3/mm^2.

As an example with a 10 mm ball, a 1 mm depth of indentation will yield a radius of 3 mm with an area of 28.27 mm^2.

Table 4
Optimum performance from F^1 with varying depths of cut (1.125 mm feed/revolution)

Depth of cut (mm)	Contact angle (deg)	Horizontal feed (mm/min)	Performance (cm^2/min)	Points in contact	Horizontal feed taken (mm/min)	Actual points	Test
5	10.1	6149	307	34.6	4000	34.1	11
10	14.2	4365	436	48.9	4000	49.3	12
15	17.5	3578	536	60.0	4000	64.5	13
20	20.2	3111	622	69.4	2000	66.0	7
25	22.6	2793	698	77.7	3000	77.4	10

Table 5
Sawing test analysis based on Brook hardness

	'E'	F (mm)	X_c (mm)	X_g (mm)	Points in 1 track	Tracks	Points in contact	Load (N)/ $X^2 \times 660$ N/mm^2	Volume removed	Calculated volume
1	10.505	0.002815	0.02957	0.2077	1.822	21.67	39.47	39.45	750	750
4	8.081	0.004728	0.03821	0.1608	1.084	27.99	30.36	30.36	750	750
2	7.111	0.006079	0.04323	0.1421	2.109	31.67	66.79	66.79	1875	1875
5	5.758	0.009180	0.05285	0.1163	1.117	38.72	43.26	43.26	1500	1500
3	5.064	0.011766	0.05958	0.1031	1.634	43.65	71.34	71.34	2813	2813
6	4.983	0.012136	0.06048	0.1016	1.268	44.30	56.16	56.16	2250	2250
11	4.545	0.014473	0.06578	0.0934	0.709	48.19	34.15	34.15	1500	1500
7	4.393	0.015438	0.06783	0.0905	1.329	49.69	66.03	66.03	3000	3000
9	4.242	0.016501	0.07001	0.0877	0.932	51.29	47.81	47.81	2250	2250
8	4.020	0.018267	0.07344	0.0836	1.404	53.80	75.52	75.52	3750	3750
12	3.283	0.026619	0.08739	0.0703	0.771	64.02	49.33	49.33	3000	3000
13	2.862	0.034110	0.09763	0.0629	0.902	71.52	64.51	64.51	4500	4500
10	2.747	0.036672	0.10080	0.0610	1.049	73.81	77.41	77.41	5625	5625

Table 6
Comparison of chip size with area of new fracture

Description	Test 1	Test 10
Radius of indentation, X_c	0.02957 mm	0.1008 mm
Track width, X_g	0.2077 mm	0.0610 mm
$X^2 = X_c \times X_g$	0.006142 mm^2	0.006142 mm^2
Indentation force (N)	4.054	4.054
Feed depth, F	0.002815 mm	0.03667 mm
Volume of $X^2 = X_c \times X_g$	0.00001729 mm^3	0.0002253 mm^3
Volume of 1 chip (F^3)	0.000000022313 mm^3	0.00004932 mm^3
New fracture on 1 chip ($6F^2$)	0.00004755 mm^2	0.008069 mm^2
Number of chips in $X^2 \times F$	775.0	4.567
Total area of new fracture	0.03685 mm^2	0.03685 mm^2
Number of cycles/s	11,544,181	886,225

Radius divided by depth = 3.0 E

$$\frac{3.333\ \mathrm{mm}^3/\mathrm{mm}^2}{3.0^2} = 0.3704\ \mathrm{mm}^3/\mathrm{mm}^2.$$

If this were a Brinell hardness test with a 3000 kg load generating an area of 28.27 mm^2, hardness would be 106.1 kg/mm^2 to displace 0.3704 mm^3

$$\frac{106.1\ \mathrm{kg}}{0.3704\ \mathrm{mm}^3} = 286.5\ \mathrm{kg\ to\ displace}\ 1\ \mathrm{mm}^3\ \mathrm{in}\ 1\ \mathrm{mm}^2.$$

All other displacements, by any size of indenter, should be proportional to this figure for tests on the same material. As an example

$$10\ \mathrm{mm}/E^2 = 1.111\ \mathrm{mm}.$$

A sphere of this diameter indented to its mid-position will have a displacement of 0.3704 mm^3/mm^2.

The ADPD of a diamond particle is used to calculate the displacement potential of a sliding indenter. Proportionality with a Brinell test on the same material will generate a modified hardness as kg/mm^2. The Brook hardness is 0.1 of this figure, as the constant base resistance of the material which will then be increased in pressure by the value of E based on depth of indentation.

The Shore hardness number is also the optimum diamond mesh size, i.e. 88.0 shore = 80/100 US mesh; 20–120 shore is the complete range of rock hardness covered by 20–120 US mesh size, but this has to be proven.

4.3. Shore hardness

The Shore hardness test[1] uses a small diamond tipped hammer dropped from a fixed height then measures the rebound height as a measure of hardness. The scale for hardness was developed from a single average test on a

[1] Atkinson–Noland & Associates Inc. Consulting Engineers, suggested method for the determination of the Shore hardness of rock. Third Draft—April 1987.

piece of quenched tool steel with an arbitrary value of 100, the achieved height was then divided into 100 equal divisions; this proves that hardness is proportional. The 'arbitrary value' is actually 100×10^4 lb/in^2; therefore, each division has a conversion value of 7.033 kg/mm^2 (Brinell).

The diamond tip is ground spherical to an approximate radius of 0.5 mm; it is then calibrated to a recognised test sample by grinding a small flat on the crown of the diamond. This only provides equality with one test sample and negates the proportionality achieved by a sphere. As a result, there are variations in conversion tables to Brinell. Proportionality may be exercised by multiplying the Shore number by 7.033 to achieve a conversion to Brinell as kg/mm^2.

The rebound height is frequently explained as being due to the elasticity of the rock, but it has not yielded a specific value. Displacement has taken place and pressure would have been generated, being contained by the elasticity of the rock. Some energy was consumed by permanent deformation, but the drop hammer is considered to be a missile, it has an energy requirement that is normally supplied by pressure. Displaced volume is not easily measured, but proportional dimensions can be obtained from Brinell.

4.4. Brinell hardness

The Brinell hardness test applies a 3000 kg load on a 10 mm ball then measures the curved area of permanent deformation via a microscope, Load divided by area = hardness as kg/mm^2. This test cannot be used for testing rock, as it will break every sample; theoretical dimensions have to be used based on Shore hardness.

Conversion of 88.0 shore $\times$ 7.033 = 618.87 kg/mm^2. Dividing 3000 kg by this hardness reveals the indented area of 4.847 mm^2. Fig. 11 indicates the details.

4.5. Optimal diamond mesh size by Shore hardness

Table 7 and 8 lists the complete narrow range of mesh sizes suitable for sawing rock, the number of particles per carat is listed along with the aperture size that will retain 90% of the particles, and this can be compared

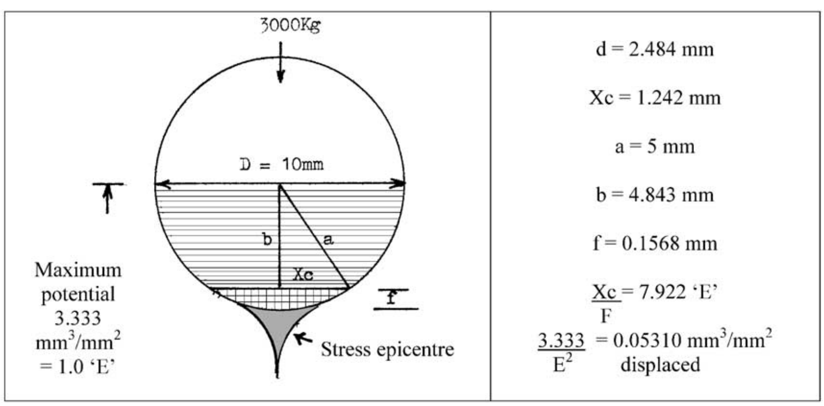


Fig. 11. The mechanism of static indentation (Brinell = 88.0 Shore).

Table 7
Optimum diamond mesh size by Shore hardness

FEPA	US mesh	PPC	90% retained on this aperture (mm)	ADPD (mm)	Displacement (mm^3/mm^2)	10 mm ϕ = 3.333 $^2\sqrt{\text{ratio}}$ = 'E'	Brinell hardness (kg/mm^2)	Brinell hardness/ 7.0327 = Shore hardness
D 851	20/25	162	0.710	0.706	0.2353	3.763	155.03	22.04
D 711	25/30	272	0.600	0.594	0.1980	4.103	180.43	25.66
D 601	30/35	461	0.500	0.498	0.1660	4.481	211.33	30.05
D 501	35/40	776	0.425	0.419	0.1397	4.885	247.40	35.18
D 426	40/45	1437	0.360	0.341	0.1137	5.415	299.46	42.58
D 356	45/50	2183	0.302	0.296	0.0987	5.812	341.99	48.63
D 301	50/60	3684	0.255	0.249	0.0831	6.337	402.84	57.28
D 251	60/70	6216	0.213	0.209	0.0697	6.917	476.20	67.71
D 213	70/80	10177	0.181	0.177	0.0591	7.516	558.78	79.45
D 181	80/100	17058	0.151	0.149	0.0497	8.192	660.13	93.87
D 151	100/120	29473	0.127	0.124	0.0413	8.980	789.32	112.24

Optimum diamond mesh size is the Shore hardness number used as the first number of 'Narrow' range of US diamond mesh sizes.

Table 8(a)
Drilling test analyses

Test	Material	RPM	Penetration (mm/min)	Feed/ revolution	Torque (N m)	Load (N)	Pressure (N/mm^2)	Brook hardness	'E'	'F' (mm)	'X_c' (mm)	'X_g' (mm)
Bit No. 510 85 concentration of 25/35 US mesh, SDA 100+												
1	Pennant sandstone	248.5	78	0.3139	49.9	1603	366	164.0	2.234	0.08718	0.1948	0.0875
2		502.3	150	0.2992	55.4	1780	427	185.6	2.300	0.08311	0.1910	0.0892
3		800.4	236	0.2948	57.6	1850	450	194.1	2.319	0.08189	0.1899	0.0898
4		999.3	316	0.3162	61.8	1985	450	202.5	2.224	0.08783	0.1953	0.0873
9	Pennant sandstone	800	145	0.1812	44.05	1415	560	203.0	2.752	0.06091	0.1676	0.1015
10		800	239	0.2987	60.7	1950	468	203.5	2.301	0.08299	0.1909	0.0893
11		801.3	324	0.4043	98.0	3148	558	203.5	2.745	0.06121	0.1680	0.1015
15	Stainton sandstone	805.8	160	0.1986	31.3	1005	363	139.1	2.611	0.06680	0.1744	0.0977
16		799.8	239	0.2988	41.5	1333	320	139.1	2.300	0.08301	0.1910	0.0893
17		800.6	317	0.3957	50.6	1625	295	139.1	2.118	0.09519	0.2016	0.0846
8a	Cornish	249.1	76	0.3051	145.1	4661	1096	482.3	2.272	0.08475	0.1926	0.0885
8b	Granite	501.8	161	0.3208	156.5	5027	1124	509.8	2.205	0.08910	0.1965	0.0868
Bit load	Pennant sandstone	800	265	0.3312	100.0	3212	736	203.5	3.419	0.04117	0.1407	0.1211
Bit No. 509 50 concentration of 40/50 US mesh, SDA 100+												
5	Cornish Granite	196.5	31	0.1577	67.9	2181	992	341.4	2.906	0.03319	0.0964	0.0637
6		398.7	70	0.1756	89.9	2888	1180	443.5	2.660	0.03881	0.1032	0.0595
7		607.5	122	0.2008	109.5	3517	1256	528.3	2.378	0.04709	0.1120	0.0548
8		809.5	155	0.1915	160.1	5143	1927	775.6	2.484	0.04371	0.1086	0.0566
12	Cornish Granite	796.6	97	0.1218	126.0	4048	2385	775.6	3.074	0.02999	0.0922	0.0666
13		809.5	155	0.1915	160.1	5143	1927	775.6	2.484	0.04371	0.1086	0.0566
14		802.9	195	0.2429	165.7	5323	1572	775.6	2.027	0.06136	0.1244	0.0494
4a	Pennant	246.9	50.3	0.2037	36.7	1179	415	176.7	2.349	0.04810	0.1130	0.0544
4b	sandstone	497.05	96.5	0.1941	43.4	1394	514	209.9	2.453	0.04466	0.1096	0.0560
4c		1005.4	198	0.1969	50.7	1629	593	244.6	2.425	0.04555	0.1105	0.0556
Bit load	Cornish Granite	800	60	0.0750	118.0	3790	3626	775.6	4.674	0.01372	0.0641	0.0958

Table 8(b)

Test	Efficiency (mm^3/W)	Velocity (m/s)	Actual (volume/s)	Estimated (volume/s)	Total tracks	Points in 1 track	Total points	Optimum points	Load 1 point (N)	Bit load (kg)	Wear (mm/m)	Point count
Bit No. 510 85 concentration of 25/35 US mesh, SDA 100+												
1	2.730	0.810	3544	3544	159.2	3.600	573.3	571.3	2.796	320		
2	2.344	1.637	6830	6830	156.2	3.600	562.4	571.3	3.164	352		
3	2.2214	2.609	10725	10724	155.3	3.600	559.0	571.3	3.310	380		
4	2.2204	3.258	14360	14360.1	159.7	3.600	575.0	571.3	3.453	296		
9	1.786	2.608	6589	6589	137.4	2.975	408.7	571.3	3.462	242	0.009	
10	2.136	2.608	10861	10861	156.1	3.600	562.0	571.3	3.470	450	0.007	
11	1.790	2.612	14724	14724	137.3	6.606	907.3	571.3	3.470	615	0.025	
15	2.753	2.627	7271	7271	142.6	2.972	423.9	571.3	2.372	153	0.005	
16	3.125	2.607	10861	10860	156.1	3.600	562.0	571.3	2.372	332	0.003	
17	3.394	2.610	14396	14396	164.8	4.157	685.3	571.3	2.372	466	0.033	
8a	0.912	0.812	3454	3454	157.4	3.600	566.8	571.3	8.224	1650		
8b	0.890	1.636	7316	7316	160.6	3.601	578.4	571.3	8.692	1863		
Bit load	1.359	2.608	12042	12042	115.1	8.046	925.8	571.3	3.470	800	0.313	1044
Bit No. 509 50 concentration of 40/50 US mesh, SDA 100+												
5	1.008	0.641	1408	1408	218.9	4.751	1040	1091	2.097	619		
6	0.847	1.300	3181	3181	234.3	4.524	1060	1091	2.724	925		
7	0.796	1.980	5544	5544	254.2	4.264	1084	1091	3.245	927		
8	0.519	2.639	7043	7043	246.4	4.380	1080	1091	4.764	1799		
12	0.419	2.597	4408	4408	209.3	4.060	850	1091	4.764	1943	0.040	
13	0.519	2.639	7043	7044	246.4	4.380	1080	1091	4.764	1799	0.078	
14	0.636	2.617	8861	8861	282.3	3.958	1117	1091	4.764	1651	0.075	1224
4a	2.409	0.805	2285	2286	256.4	4.235	1086	1091	1.086	139		
4b	1.941	1.620	4385	4385	248.7	4.347	1081	1091	1.290	207		
4c	1.686	3.277	8997	8998	250.7	4.324	1084	1091	1.502	284		
Bit load	0.276	2.608	2726	2727	145.5	5.467	796	1091	4.764	1995	0.280	1728

with the theoretical ADPD for which a maximum displacement potential has been calculated. To find the relation with Brinell hardness, the potential of a 10 mm ball is divided by the potential of each mesh size to reveal E^2, the square root then giving the value of E, which can be related to the dimensions of a Brinell test from Fig. 10 to reveal the area of indentation and hardness by dividing 3000 kg by the area. By dividing Brinell by 7.033, it reveals the Shore hardness that is optimum to each mesh size.

By using a high quality diamond with a mesh size larger than optimum means that the pressure generated will be higher than normal. If the tool has ample stability, this may not be a detriment as it can be balanced with a larger chip size with increased efficiency. It is not recommended for use on hard rock, as high pressure will also generate very high vertical force F_z that can cause blade deviation. High point loading should be avoided, maximum performance is achieved by increasing the depth of the cut, and this increases blade stability allowing quite high total loads to be supported with stability.

Volumetric displacement also explains why worn diamond particles can cause massive increases in energy requirement; 2% loss in volume through wear can increase pressure generation by 200%, but this can increase F_z by more than 300%.

Volumetric displacement also explains the mechanism of friable diamond, discarding part of the indented mass reduces the generation of pressure, this in turn will improve efficiency but it is still an action of confined crushing which will yield no advantage to the tool user that cannot be better achieved by some other means.

4.6. Brook hardness

Brook hardness measures the volumetric displacement of a specified diamond mesh size, and then relates this proportionally to the pressure generated by a theoretical Brinell test (converted from Shore) for the same material. The actual figure that constitutes Brook hardness is 0.1 of that calculated, as this will be the constant base resistance encountered by a single diamond particle of the specified mesh size as an indentation load which is that used to calculate torque (N m). The depth of indentation produces a constant formula for the calculation of E which is a compression ratio for the generation of pressure, i.e. Brook hardness $\times E$ = pressure N/mm^2; $\frac{1}{4}$ADPD $= X$, Brook hardness $\times X^2$ = indentation load (N).

Brook hardness replaces the potential for an unknown large variability and gives the specific optimal value. As comparison tests have been limited, it cannot be claimed that this method is applicable to every type of rock.

5. Core drilling

5.1. Feed per revolution as an alternative to bit load

In 1992, DeBeers agreed to carry out a series of drilling tests for the author to confirm the accuracy of feed per revolution as a means of control for diamond particles sawing rock. As a benchmark for normal bit load penetration, it was decided to use a paper published in Industrial Diamond Review 5/90, 'Segment Wear on Diamond Impregnated Mining Bits' [3] where two types of NQWL core bits were used for drilling Cornish granite and Pennant sandstone. The same drill rig would be used, with identical tools on the same material; Stainton sandstone was added to give additional data.

The optimum feed was stated for penetration by feed per revolution at 800 rpm; this was repeated with reduced feed and then with increased feed above optimum to provide a comparison. Approximately constant feed was applied with variations of RPM.

Rates of wear in mm/m were given for some of these tests. The rates of wear for bit load penetration were measured by diamond particle exposure. The total number of particles was not given in the paper, but these were obtained verbally for both bit load tests; only one fully comparative analysis is available for Cornish granite with penetration by feed per revolution.

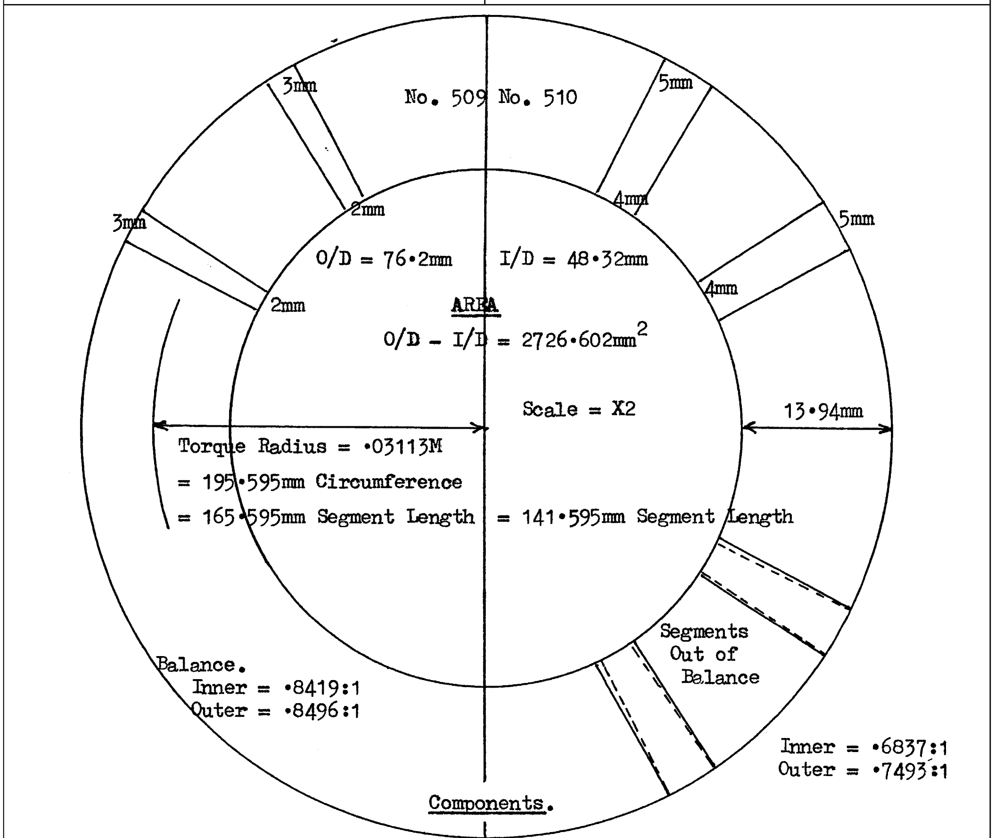
Reference had to be made to a second paper, 'Selection of Diamond Bit Type for Hard Rock Drilling' [4], to obtain wear rates of mm/m for drilling Pennant sandstone. This paper also highlighted irregular crown wear whilst drilling Pennant sandstone—the cause being the waterways not being a true segment of a circle, increasing the work load of the diamond particles on the inner edge, confirmed by large bond tails in the photographs in [3].

Suggestions were also made that only 25% of the particles were in a working zone, based on another paper 'Investigations and Predictions of Diamond Wear when Sawing' [5]. This paper was based on a circular saw cutting Cornish granite at 250 cm^2/min when the capability of the diamond content was 1000 cm^2/min but, because the design of the tool was inappropriate, it could not have supported the load to achieve this figure. In this instance, only 25% of the diamonds would be working, it does not apply to drilling, and hopefully detailed analysis given later will yield some satisfactory answers.

5.2. The potential of NQWL core bits

Fig. 12 details the potential of bit number 509, which had 50 concentration (12.5%) of 40/50 US mesh, SDA 100+ quality. Bit number 510 had 85 concentration (21.25%) of 25/35 US mesh, SDA 100+ quality. Optimal feed per revolution is specified for each bit;

50 Concentration = 12.5% 40/50 Mesh = 1850 PPC SDA 100+	85 Concentration = 21.25% 25/35 Mesh = 400 PPC SDA 100+



$V^1 = 0.0308\ mm^3$ ADPD = 0.3135 mm X = ¼ ADPD = 0.07837 mm $X^2 = 0.006142\ mm^2$ F^1 = 1/6th ADPD = 0.05249 mm Efficiency of F^1 = 2.236 'E' Xc = F^1 x E = 0.1168 mm Xg = Track width = $\frac{X^2}{Xc}$ = 0.05257 mm $\frac{165.6 \times X^2 \times 12.5\%}{0.03081\ mm^3}$ = 4.127 points in one track $\frac{13.94\ mm}{Xg}$ = 265.1 tracks = 1092 points in contact 0.2156 mm feed per revolution	$V^1 = 0.1425\ mm^3$ ADPD = 0.5223 mm X = ¼ ADPD = 0.1306 mm $X^2 = 0.01705\ mm^2$ F^1 = 1/6th ADPD = 0.0870 mm Efficiency of F^1 = 2.236 'E' Xc = F^1 x E = 0.1946 mm Xg = Track width = $\frac{X^2}{Xc}$ = 0.08760 mm $\frac{141.6 \times X^2 \times 21.25\%}{0.1425\ mm^3}$ = 3.600 points in one track $\frac{13.94\ mm}{Xg}$ = 159.1 tracks = 571.3 points in contact 0.3134 mm feed per revolution

Fig. 12. Potential of NQWL core bits.

this is a constant figure that would apply whatever type of rock were being drilled.

5.3. Methods of analysis

The analysis of all the drill tests evaluates feed per revolution from the diamond content of a tool. Fig. 12 shows how this was achieved. The following data show how torque and performance is broken down for analysis.

1. Torque (N m) divided by the tool radius of 0.03113 m reveals the load (N),
2. Feed per revolution × 13.94 mm tool width = excavated area (mm²),
3. Load (N) divided by the excavated area (mm²) = pressure (N/mm²),
4. Pressure (N/mm²) divided by Brook hardness (N/mm²) = E,
5. E is the pressure generating mechanism described in Fig. 9,
6. Given E and ADPD, point feed F can be calculated from Fig. 10,
7. $E \times F = X_c$, X^2 divided by $X_c = X_g$ (track or groove width),

8. 1000 mm^3 divided by pressure (N/mm^2) = efficiency mm^3/s by 1 W,
9. 0.03113 m radius × 2 × π × rpm/60 = velocity (m/s),
10. 2727 mm^2 tool area x penetration (mm/s) = volume removed in 1 s,
11. $X_g \times F \times$ total points × velocity (mm/s) = volume removed in 1 s,
12. 13.94 mm tool width divided by X_g = total tracks,
13. Feed per revolution divided by point feed F = points in 1 track,
14. Total tracks × points in 1 track = total points in contact,
15. Total load (N) divided by load for 1 diamond particle = total points in contact,
16. Brook hardness (N/mm^2) × X^2 = load (N) for 1 diamond particle.

5.4. Variability of brook hardness at low velocity

The variable reaction of the force vector appears to start at about 10 m/s. Changing the point of contact between the chip and tip of the epicentre improves the efficiency of pressure transfer because the requirement of chip fracture has not changed and the demand for energy input is reduced. In turn, this shows that Brook hardness has also reduced, which can be misleading without understanding the cause.

At a velocity above 10 m/s, 40/50 US mesh penetrating Cornish granite would have a Brook hardness (proportional to Brinell) of 1564 N/mm^2 and the 25/35 US mesh would have had a Brook hardness of 2606 N/mm^2. Increasing these figures to pressure with the introduction of E would introduce a vertical force F_z of over large proportions. This explains the current difficulty of circular sawing hard granite where attempts to use 40/50 US mesh requires the use of minimum contact lengths with poor performance, yet it still yields high tool costs with deviation problems that are never far away. Reducing the diamond mesh size below that of optimum at low velocity does not appear to improve energy efficiency but can yield very low F_z loads. As the drill bit can support high bit loads, high concentrations of large diamond mesh sizes could be used as a universal bit capable of drilling every type of rock at optimum feed per revolution, simple by controlling the RPM, as this also controls the torque and the resultant bit load.

5.5. Bit load as the cause of excessive wear

The requirement of bit load as a means of penetration has opposite effects between granite and sandstone: increasing the feed rate of granite reduces the generation of vertical force F_z which is the major component of bit load; increased feed on sandstone will increase vertical force F_z, but at a very much reduced level to that of granite. Assuming that there is no existing knowledge of the reactions to reduced velocity, bit load can soon be excessive putting the bond metal in contact with the rock causing rapid tool wear prematurely allowing diamond particles to drop out after very little use.

Maximum exposure with maximum indentation creates a complete breakdown in what had previously been shown to be a dependable mechanism based on regular track paths. More diamond points are brought into contact in each track path; this splits the feed reducing the efficiency of each point, also widening the track bringing even more points into play, but many are unable to take any feed as they are protected by their neighbours. Tests 11 and 17 show this breakdown under control of feed per revolution and how it increased tool wear, but the 800 kg bit load of the earlier tests is double what it should be and is increasing wear by 4400% above Test 10. No wear rates are available for Test 4, but all the results are acceptable. Feed per revolution should be considered as an alternative to bit load penetration when drilling.

6. Frame sawing with diamond

6.1. Common drilling parameters

Bit number 509 with 50 concentrations of 40/50 US mesh had a surface area of 2300 mm^2; a frame saw blade with 23 segments, 20 mm long × 5 mm wide has a surface area of 2300 mm^2. This concentration, mesh size and diamond quality is not excessive as the author used 90 concentration of 40/50 US mesh, DSN 47 which is a superior hardness, for frame sawing Cornish granite with 23 segments at 90 mm centres.

The peak velocity of the reciprocating frame is the constant crank velocity; a 500 mm stroke@100 RPM = 2.618 m/s. As feed is normally applied at a constant rate, the actual feed depth taken at maximum velocity is minimum and well below any drilling tests, so that the generation of vertical force F_z will be maximum and will easily achieve 2000 kg which cannot be supported on a blade that can be 4 m long with a section of $180 \times 3\ mm^2$.

By reducing the stroke length to 130 mm with $\frac{100}{120}$ strokes/min, the peak velocity is reduced to about 0.5 m/s and held for only a short time; this enabled a downfeed of 300 mm/h on a 2.0 m block length of Cornish granite for a segment cost of about £2.00/m^2 of slab. By reducing the velocity, the total energy input is minimized and the vertical force F_z reduced to loads that can be supported by a blade of standard dimensions, provided that the method of pre-stressing is modified.

The detail of this modification is omitted here, as it may be required for a future patent application.

6.2. The potential for frame saws

The ease or difficulty by which rock is currently being frame sawn by diamond can be expressed by its Shore hardness and a resulting Brook hardness at low velocity. It is anticipated that the load-bearing capability of a frame saw blade can be increased by 50–100%; without any modification to existing machines, diamond concentration can be increased to extend blade life and improve performance.

It has already been shown that large diamond particles (surface set) can be used at reduced velocity with virtually no wear on sandstone, but when the frame saw design that can cut hard granite is considered, there is the potential to use synthetic diamond compacts for many other types of rock to achieve improved performance.

Loose abrasive swing saws, that are currently sawing granite, could possibly be converted to diamond; the swing action is not a severe problem as this can be accommodated by segment design. The stroke length will have to be shortened, but all other aspects should be satisfactory, even blade tensioning, as it is anticipated that the maximum tension per blade will be about 4 tonnes.

7. Conclusions

The problem of improving the efficiency of rock sawing was not resolved initially by the application of existing theory. Indeed, sometimes long-standing problems that apparently have no solution can be resolved by radical new approaches—as has been presented in this paper. Using the principles, the author has increased extraction and processing of a single unit by ten times through optimized diamond cutting performance. Thus, it is hoped that the application of the principles outlined here will lead to overall increased production capability in the rock sawing industry.

Appendix A. Glossary of terms in the rock sawing context

A.1. Rock strengths

Crushing strength is the most popular strength—where a sawn cube of rock is loaded on the upper surface whilst all edges are completely free. The load that collapses the sample is divided by the surface area of one side to reveal the unconfined crushing strength as load per unit area.

Confined crushing strength remains an undefined resistance which can be variable, but has been measured at 45 times greater than the unconfined crushing strength of Orienta granite. In this paper it is termed the 'Brook hardness', as this is the mechanism related to hardness testing, rock fracture, and a constant base resistance to volumetric displacement.

Shear strength has been measured using a hydraulic rock splitter by dividing the ram load by the surface area of fracture; it is about $\frac{1}{40}$th of the unconfined crushing strength and can be considered to be the energy requirement of rock fracture, but to optimise the process the shape of the indenter is critical.

Tensile strength is usually regarded as the result of a fracture by a Brazilian disc tester, which is an enlarged version is the hydraulic rock splitter. An alternative version applies a conversion formula to the Shore hardness number, but as steel and rock can have equal hardness, accuracy of the result seems doubtful. Tensile strength can be considered as the fracture point from bending; cleaving slate is dependent upon bending strength, and a chip of rock is a manifestation of its own tensile strength. A chip size ratio for granite is 4:1, where length and width are four times greater than the thickness.

Hardness is actually the confined crushing strength of rock, but the tests that define 'hardness' have to be examined. Comparative numbers are useless when a specific value is required; this must reveal equal hardness from at least two tests by different methods of indentation. Shore and Brinell can show this equality, but Rockwell is introduced to show the recovery of the rock when the indentation load is removed.

A.2. Fracture mechanism

Rock fracture. Fracture in its crudest form is achieved by a heavy blow from a hammer, which is identical to the Shore hardness test. The aim is to be able to predict the energy requirement to achieve a fracture from the ability of a rock to generate pressure from volumetric displacement. The paper shows how diamond particles do this and how the process can be controlled, but as rock sawing is still considered to be an indefinable process, it is better to explain the full details of hardness testing and rock fracture, and then state that diamond particles use the same mechanism.

Shapes of indenter. A point gives the impression of being able to focus stress, but in fact it achieves little penetration before surface deformation or premature fracture becomes apparent. A sphere on the other hand requires very little indentation to generate a stress 'epicentre' that has the ability to penetrate the rock for a considerable distance. When the load is sufficient, this is the fracture mechanism for rock. A rock splitter with a 2.5 mm radius breaker bar was used to fracture a fine grain sandstone with a 150 mm deep fracture, a stress epicentre 20 mm long was visible after the fracture firmly attached to the breaker bar. The crushing strength was

59.63 N/mm^2, the shear strength was1.48 N/mm^2, $\frac{1}{40}$th of the crushing strength.

Stress epicentre. The cross section of the epicentre is identical to the section of a hollow ground 'cut throat' razor, where indentation and displaced volume destroy the tensile fabric of the rock, grain size appears to be reduced and it is possible that density is greater than the parent rock to allow penetration. Whilst under pressure the epicentre will have a degree of plasticity to enable it to transfer stress similar to hydraulics, but as it does not have the same efficiency as a fluid, it can be expected that pressure generated will diminish from base to tip. The vertical force is converted to horizontal pressure by volumetric displacement, this pressure and the surface area of the epicentre is the fracture mechanism when the load is sufficient; loads that do not achieve fracture can be used to determine the ability of rock to generate pressure by volumetric displacement measured as 1oad to displace 1 mm^3 in 1mm^2; then all other displacements will be proportional to this figure. A sphere is not designed to generate a fracture in a specific direction, but a circular rod introduces direction. A Brazilian disc tester with a radiused indenter should produce a straight fracture and a resistance that is lower than that produced by a point, but the tensile strength is a different quantity.

A.3. Hardness tests

Brinell hardness. A load of 3000 kg is applied on a 10 mm ball; the diameter of permanent indentation is measured via a microscope; a specified formula is then used to measure the curved surface area of contact; load divided by this area is considered to be 'hardness' as kg/mm^2. If 'hardness' is considered as variable 'pressure' generated by variable volumetric displacement, the action is confined crushing, but the material being tested must also have a constant value that is different to 'hardness'. Tests that are proportional are explained as being performed by balls that can deform to explain indentation diameters that are larger than anticipated. Proportionality does not generate equal hardness as we know it, but it will reveal the constant base resistance that is not currently recognised.

Shore hardness. A small hammer with 0.5 mm radius diamond tip is dropped from a fixed height in a glass tube, the rebound height is the measure of 'hardness'. When testing rock, 50–100 tests are conducted on each sample to produce an average for the different mineral strengths contained. The scale of hardness was developed from a test on quenched tool steel with an arbitrary value of 100; the rebound height was then divided into 100 equal divisions; therefore, 'hardness' is proportional—with each division having a conversion value to Brinell of 7.033 kg/mm^2. Proportionality is explained in a table where the potential for displacement by spheres in the range of 20–120 US mesh is compared to Shore hardness 20–120, as a conversion to Brinell and the volume displaced by equal hardness. Brinell hardness as kg/mm^2 divided by the volume displaced, as mm^3/mm^2, reveals the constant resistance of the rock being tested.

Rockwell hardness. There are variants to this test, but basically a pre-load is applied to measure the starting point of zero indentation; the main load is then applied, held for a short period, then removed to measure the depth of permanent deformation. The amount of recovery is currently ignored for hardness, but when sawing or drilling rock with diamond tools, this recovery is vertical force, F_z, for sawing, and the bit load for drilling. The torque load is the requirement of the indentation mechanism with excavation efficiency being measured from the variable pressure or resistance. Vertical force, F_z, is proportional to this pressure and is important as it has the potential to deviate every type of tool sawing rock.

A.4. Rock type

Orienta granite has a crushing strength of 148.2 N/mm^2, Shore hardness is 88.0, by conversion tables this is 609 kg/mm^2 Brinell HB, 61.0 Rockwell HRc, 775 Vickers HV. Constant base resistance of Brook hardness is 660 N/mm^2, but sawing test analysis revealed a pressure of 6933 N/mm^2, and this is variable if the size of the diamond particles is changed. Brinell hardness gives the appearance of being a specific value close to the pressure of minimum efficiency and Brook hardness, but if either the load or the diameter of the indenter is changed, the Brinell 'hardness' will be different.

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