Laboratory Comparison of Mini-discs with Point-attack Picks

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\textbf{Abstract.} The selection of the cutter type is of crucial importance to maximise the advantages of mechanical rock excavation systems. Specific energy (SE), cutter forces, and rock properties are used to decide what type of cutter is most suitable for economical excavation of the rock based on laboratory rock cutting tests. This study is concerned with the preliminary results of an ongoing rock cutting program in which a mini-disc has been compared with a point-attack pick in laboratory linear cutting tests simulating a cutterhead on a Helidon sandstone block. Analysis of the preliminary results has shown that the mini-disc experienced lower mean cutting forces and was seven times more efficient than the pick in first layer cuts. However, the mini-disc had mean normal forces 1.5 times higher than the pick. Additionally, first layer cuts taken on the trimmed surfaces required more forces and SE than completely relieved cuts in pick cutting.

\textbf{Introduction}

Power consumption of mechanical excavators depends on the specific energy (SE) of cutting and hence the level of cutter forces. SE is the amount of energy consumed to excavate a unit volume (or mass) of rock material using a particular cutter. The lower SE, the less power is needed to be installed on the machine employing that cutter. In other words, lower SE means that a given machine will produce more cut material for a given power consumption, or that a smaller/less expensive machine may be used to produce the required amount of cut material. Generally, for a given production rate, a mechanical excavator equipped with a cutter that is able to produce a lower SE value would be preferred as it provides a high cutting efficiency.

SE parameter is clearly specific to both the machine with its cutter type and the rock. There are several types of mechanical cutters used to cut the rock among which discs and picks have the most common applications in practice. Fig 1 shows SE as a function of particle size generated by mechanical excavators equipped with discs and picks [1]. As can be seen from Fig 1, SE reduces drastically as the chip size increase. This means that the bigger the mean chip size the lower SE and the more efficient the mechanical excavation process becomes. Fig 1 also shows that machines equipped with discs have a lower SE and produce larger rock chips than those equipped with picks.

This study is concerned with the preliminary results of ongoing linear rock cutting tests conducted on a Helidon sandstone sample in CSIRO rock cutting laboratories in which the cutting efficiency of a steel type mini-disc has been compared with a tungsten carbide (WC)-tipped point-attack pick under the same cutting conditions.

\textbf{Disc cutting versus Pick cutting}

There are two types of mechanical rock cutting tools, those that roll (discs) and those that are dragged (drag tools) (Fig 2). Tools in the latter category often are termed picks. The great majority of the rock cutting/drilling tools employed in mining and tunnelling operations today are indenters that roll. All types of roller cutters like discs are indenters that break the rock in indentation. The distinction between the two types of tools is that a disc breaks the rock by applying a force that is, predominantly, in a direction normal to the rock surface. In contrast, the main force applied to a sharp pick to affect rock breakage is in a direction approximately parallel to the rock surface [2,3].
Discs are known to be less efficient than picks as picks break the rock in tensile mode whereas discs break the rock in compressive and under a confined mode. Most rocks behave as brittle materials, which are about an order of magnitude weaker in tension than they are in compression. That is why the energy spent by a pick is (theoretically) low because only a small amount of work is done in rock compression by this tool. Crushing of the rock requires a very large amount of energy to form rock chips with discs [2,4]. Evans [5] reported that for the cutter geometries that are likely to be found in practice, the ratio of SE for disc cutting to SE for pick cutting is about 1 for shaly rocks whereas it is between 2 and 5 for different sandstones. However, Ozdemir [1] reported that the discs are more efficient than the picks depending on the data collected from various types of mechanical excavators operating in different rock formations over many years. It is also well known that the cutting efficiency is a function of the shape and size of the cutter and the mode of cutting.

**Experimental Setup**

Linear rock cutting tests have been carried out on CSIRO rock cutting planer (Fig. 3a) to compare the cutting performance of two types of cutters: wedge type steel mini-disc and WC-tipped point-attack pick (Fig. 3b and 3c). The tests were conducted on a large (1800×450×450 mm) Helidon sandstone block with clayey matrix (Unconfined compressive strength= 30 MPa, Brazilian tensile strength= 4 MPa, Cerchar abrasivity index= 1). It is mainly aimed to carry out such a comparison on hard and abrasive Harcourt granite. With the tests on Helidon sandstone, it is also aimed to understand if it is possible to cut Harcourt granite under the proposed experimental conditions without damaging the rock cutting planer. A constant depth of cut of 5 mm and a constant cutting speed of 1.1 m/s have been used in all tests. A Sandvik P7AU point-attack pick with 90° primary tip
angle and 22 mm tip diameter has been used in the study. The pick was set at an attack angle of 55°. A mini-disc made up of high-speed steel with 100 mm diameter has been used in this study.

![Figure 3](image-url)

The main objective of the linear rock cutting tests was to compare the performance of a mini-disc with a pick in the laboratory simulation of a cutting action of a cutterhead when laced in a 2-start, 1 tool per line arrangement with 6 cutters using a single cutter. During the tests, the rock block was initially trimmed to obtain a flat cutting surface on which the first sequence of cuts, i.e. first layer cut, was performed. These cuts were then followed by second layer cuts in the form of successive layers representing the cutting perimeter. These two layers of cuts were taken to reach the desired cutting regime to simulate the actual cutting action of the cutters on a roadheader cutterhead. The third layer cuts, representing the first layer cuts at the second revolution of the cutterhead, have been taken as the completely relieved cuts. There was no trimming in between these three layers of cuts.

Line spacing values for the point-attack pick were 10, 20, 30, and 40 mm whereas 15, 25, 35, and 45 mm of line spacing were used in mini-disc cutting tests. These spacing values resulted in spacing-to-depth (s/d) ratios of 2, 4, 6, and 8 for the pick and ratios of 3, 5, 7, and 9 for the mini-disc. Line spacing values for the mini-disc have been selected wider than those for the pick considering the wider spacings that can be achieved with mini-discs for efficient cutting [6] and the width of the rock block available for this. Cut spacing (spacing between the grooves cut by the picks positioned on the same spiral) was two times the line spacing (spacing between neighbouring grooves regardless of the spiral arrangement) for both the point-attack pick and the mini-disc.

3D cutter forces have been measured for each cut using a triaxial force dynamometer. SE of cutting involved the collection and weighing of all cutting debris from the cut. Then the yield was calculated using the density of the rock, the weight of the cut material, and the cutting length. SE of each cutting was then calculated by dividing mean cutting force by the yield for both the pick and the mini-disc. Each cut has been repeated at least once.

**Experimental Results**

The variations in the mean cutting forces (MCF) and mean normal forces (MNF) acting on the cutters with spacing-to-depth ratio are given in Figs. 4 and 5, respectively. MCF and MNF on the point-attack pick tended to increase continually with increasing s/d ratios in completely relieved cuts (Figs. 4a and 5a). However, the gradual increase in MCF and MNF on the point-attack pick was
followed by a rapid increase after s/d ratio of 6 in completely relieved cuts (Figs. 4a). On the other hand, in first layer cuts, MCF acting on both the point-attack pick and the mini-disc changed with s/d ratio in such a manner that it first increased gradually and then tended to level out after s/d ratios of about 4-5 (Fig. 4b). Similarly, MNF acting on the point-attack pick increased gradually until s/d ratio of about 4 after which it tended to level out (Fig. 5b). However, MNF on the mini-disc tended to increase rapidly until s/d ratio of 5 after which it tended to level out (Fig. 5b).

Forces experienced by the point-attack pick were always higher in first layer cuts when compared with the completely relieved cuts (Figs. 4 and 5). Additionally, linear cutting of Helidon sandstone at 5 mm depth of cut with the point-attack pick in first layer cuts and completely relieved cuts resulted in similar MCF and MNF values, respectively, being typical to weak rock cutting.

MCF values experienced by the mini-disc were about 4 times less than those experienced by the point-attack pick in first layer cuts (Fig. 4b). However, limited data currently available for the mini-disc indicated that the MNF on the mini-disc at 25 and 35 mm line spacings was above 20 kN in first layer cuts (Fig. 5b). There have been difficulties in maintaining constant depth of cut of 5 mm during mini-disc cutting tests especially after the first layer cuts mainly due to higher MNF values.

![Figure 4](image1.png)

Figure 4 (a) Changes in MCF with s/d ratio for completely relieved cuts with the point-attack pick (b) Changes in MCF with s/d ratio for first layer cuts with the mini-disc and the pick

![Figure 5](image2.png)

Figure 5 (a) Changes in MNF with s/d ratio for completely relieved cuts with the point-attack pick (b) Changes in MNF with s/d ratio for first layer cuts with the mini-disc and the pick

The relationship between s/d and SE in completely relieved cuts for the point-attack pick is given in Fig. 6a. As can be seen from Fig. 6a, SE decreased gradually with s/d until a minimum at s/d of 5 after which it gradually increased with increasing s/d ratio. Fig. 6a also shows that the optimum s/d ratio for cutting Helidon sandstone at 5 mm depth of cut is about 5 for completely relieved cuts.

The calculated SE values for first layer cuts are given for both cutters in Fig. 6b. In first layer cuts with both the point-attack pick and the mini-disc, SE showed gradual increase towards s/d ratio
of 4-5 and then it tended to level out. As can bee seen from Figure 6b, the ratio of SE for disc cutting to SE for pick cutting in trimmed surface cuts is about 7 for Helidon sandstone. Since the mini-disc cutting tests are still in progress, the cutting results from the completely relieved cut experiments with the mini-disc could not be given in Figs. 4 to 6.

Cutting data currently available has also shown that SE values calculated for completely relieved cuts have always been less than the first layer cuts for the point-attack pick. SE values calculated for point-attack pick in completely relieved cuts occurred between 10 and 14 MJ/m$^3$ band whereas first layer cuts generated SE values varying between 145 and 185 MJ/m$^3$ (Figs. 6a and b). Completely relieved cuts with the point-attack pick have also generated smaller SE values than those generated by the second layer cuts.

![Specific Energy in Completely Relieved Cuts](image1)

![Specific Energy in First Layer Cuts](image2)

**Figure 6** (a) Changes in SE with s/d ratio for completely relieved cuts with the point-attack pick (b) Changes in SE with s/d ratio for first layer cuts with the mini-disc and the point-attack pick

**Discussion**

Preliminary results of the cutterhead simulation tests with a single cutter have shown that the variation of SE depends mainly on the interaction between the neighbouring cuts. This interaction is a function of the line spacing at constant depth of cut. An almost constant level is reached in SE when no interaction occurs. In first layer cutting experiments with the point-attack pick, for line spacing values greater than about s/d ratio of 5, no interaction is likely to occur at 5 mm depth of cut. After that s/d ratio, SE values tend to show no change with increasing s/d ratio.

However, the same situation has not been observed with completely relieved cutting experiments with the point-attack pick as SE has continuously varied for s/d values greater than 5-6. The main reason for this may be attributed to the nature of the relieved cutting mode where the cutters cut in the middle of the preceding cuts as seen in field operation of the cutterheads. In this cutting mode, the position of the cutter tip is closer to the free surface and hence less confined. That is why, unlike first layer cuts, loss of interaction does not have an immediate effect on SE up to a certain line spacing value in completely relieved cuts. This is probably because successive cuts prevent the occurrence of the ridges on the rock surface. Those ridges tend to isolate the grooves from each other as seen in first layer cuts. This also explains why both MCF and MNF acting on the point-attack pick in completely relieved cuts is less than those occurred in first layer cuts.

The mini-disc is more efficient than the point-attack pick in cutting Helidon sandstone when first layer cuts are considered because it generates less SE. However, this may not be true for completely relieved cuts because of the reasons mentioned above. If only the results of the first layer cuts are considered, even though it is not recommended, it may be said that a cutterhead equipped with mini-discs can achieve higher advance rates than a cutterhead equipped with point-attack pick for the same machine power for cutting Helidon sandstone. Cutting coefficient (ratio of MCF to MNF) calculated for the point-attack pick is about 1.03 whereas it is about 0.18 for the mini disc, indicating higher torque requirements for a roadheader cutterhead when equipped with point-attack
picks. However, very high normal forces typically acting on mini-discs can be a problem in the field even for this soft rock because a heavier machine may be needed to provide higher thrust necessary for keeping the mini-discs in desired depth of cut. SE of cutting is calculated using MCF values for both the pick and the mini-disc. However, the main force causing rock breakage in disc cutting is MNF and the force requirement of the disc to achieve a given depth of cut is directly proportional to the contact area between the disc and the rock under the disc. Therefore, another way of calculating SE should be found out for disc cutting.

Conclusions

The cutting efficiency in any rock cutting operation is measured by its SE. Therefore, the main objective in designing a cutterhead of a particular mechanical excavator with a given power rating which will be used in a specific rock environment is to minimize SE requirements to achieve the highest advance rate. Likewise, a mechanical excavator with a properly designed cutterhead will have a lower SE and thus it will require lower cutting force, torque and power for a given advance rate. Therefore, selecting the most efficient cutter type and then mounting the selected cutters in an optimum cutterhead layout is of crucial importance to achieve the highest advance rates at the lowest SE level. This is simply because the cutter and its tip material are the major limitations for power transfer from machinery to the rock. Both the cutter body and the cutter tip must withstand the entire power transfer that occurs in rock cutting processes.

If SE can be determined prior to the excavation, then it is very useful because the volumetric rate of excavation is proportional to the power transmitted through the cutters to the rock. Hence, if SE and machine power are known, then the advance rate of rock excavation can be calculated. However, the determination of SE has mostly been limited to the parallel first layer cuts at equal depth so far. This study has clearly shown that cutterhead simulation experiments must be conducted rather than the cutting tests on trimmed rock surfaces in order to get realistic SE and cutter force values in designing cutterheads of different types of mechanical excavators such as surface miners, roadheaders, longwall shearsers, and continuous miners for higher advance rates.

The mini-discs are very efficient type of cutters that can be used in hard rocks. They can also excavate soft rocks efficiently except plastic clayey ones where chipping may not occur between adjacent cutter paths. They offer many advantages over other cutter types. These advantages include high cutting efficiency and advance rates, and robustness. Because of their high efficiency, they have very low cutter cost. However, high advance rates with the mini-discs can be limited by the bearing capacity, the machine weight to provide the required thrust and wear.

References


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