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A state-of-the-art review of mechanical rock excavation technologies

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Abstract

The first step in mining activities is rock excavation in both mine development and production. Constant pressure for cost reduction and creating an improved/safe work environment for personnel has naturally resulted in increased use of mechanical excavation systems in many mining operations. Also, mechanical excavation and mining is more compatible with automation, meaning possibility of reduction in number of people in the active underground mines. This factor plays a major role in selection of mining systems especially considering the dire shortage of skilled labour in the industry. While these systems are an integral part of mining activities in underground soft rock mining (coal, salt, potash, trona etc.), there is a need for developing new approaches and machinery for use in the underground hard rock mining. This paper will offer a review of current and emerging technologies for mechanical hard rock excavation, including disc cutting technology, drag picks, mini-disc, and activated/oscillating disc cutter. A review of general guidelines for assessment of the potentials of new research and development on this topic and evaluation of emerging technologies for a specific mining application will also be offered.

Keywords: *Mechanical rock cutting, Excavation, Rock properties, Rock breakage, Tunnel Boring Machines.*

1. Introduction

Hard rock mining industry is experiencing a major transformation due to the dynamic of the mining industry and market for natural resources and related commodities. More mines are moving underground as the open pit reserves extend to deeper elevations and the use of new techniques has led to discovery of deeper ore bodies. In the 19th Century hard rock mining was mostly underground, focused on narrow vein extraction. In the 20th Century the mining industry was characterised by large-scale surface operations. In the 21st century, the industry is rapidly moving back underground as few new major near-surface deposits have been found and the older deposits are becoming too deep to mine by open pit methods. Current underground metal production is estimated around 60,000 ton per day but it would be increased at 8 times by 2020 [1].

The new underground mines are being developed as bulk operations moving very large tonnages, using caving (mostly block caving) operations. Caving methods have very low extraction (operating) costs but a very high up-front capital expenditure for mine development – mostly tunneling. Moreover, there is a high price tag associated with subsequent crushing and processing of the material for metal extraction. Part of this cost (hauling and processing) can be avoided if selective mining could be implemented. Today, most of the developments are almost exclusively performed using drill-and-blast methods with an average advance rate of only about 4-6 m a day. However, experience with TBMs can routinely achieve daily advance of over 20 metres and in many cases 40 m/day [2], which is not practically possible by drill-and-blast operations. In fact the world record for TBM daily advance is about 170 m set in an operation in Australia [3].

Meanwhile, TBMs are capital intensive, too massive and consequently too inflexible, and site specific, thus unsuited for general use in mine development. These factors are driving a renewed push by the industry to develop a mechanised excavation system that can achieve higher advance rates and provide for better and safer work environment. In addition any such system is expected to allow for higher degree of automation, high quality of tunnel walls as produced by a TBM without having the same constraints – particularly the large turning radius. Another issue is the shape of tunnel excavated by TBM which is circular, which is not favoured by mining industry, where a flat invert is preferred. The ability to attack harder rock formations is yet one more demand for such system. Rostami provided a review of the hard rock excavation technologies and use of TBMs in underground mining applications that is relevant to this discussion [4]. Such an excavation system is sought by and would immediately be adopted by the mining industry. The goal is to achieve Rapid, Safe and Reliable Mine Development. Accessing an ore-body quickly has obvious beneficial implications on NPV. This means that some mining companies are normally prepared to invest on development of new mechanised mining systems. The market potential is very large. It is estimated that for development of block and panel caving operations around the world, more than 1100 km of tunnel will be required, over the next two decades [2]. Therefore, it is worthwhile to review the state of the art of hard rock mechanical excavation system in to explore its potential areas for future researches and developments.

2. Fundamentals of rock cutting

The basic premise of rock fragmentation is to overcome intergranular bindings between the grains and finally disintegrate the rock. This can be done in many ways, including use of mechanical tools, laser to heat and melt the rock or pulsated laser to resonate and break it into peaces, microwave induced heat and thermal stresses, electrical systems and shocks such as plasma explosion, and finally by erosion method such as water jet. Some of these methods are considered novel techniques and some have already made it to the main stream rock excavation systems. Among these methods, mechanical rock excavation and water jet has been proven successful and related systems are commercially available. Mechanical rock cutting is based on inducing stresses in the rock medium that exceeds the rock strength values to cause cracking and chip formation.

There are mainly two types of mechanical rock cutting tools – drag bits, or picks, and indenters, including roller cutters. The difference between the two systems is the way that the tool penetrates the rock. In the case of a drag bit the tool is moved across the rock surface at a depth that is called penetration (Figure 1a). For a sharp drag bit the principal component of force is in the direction of motion, termed the bit cutting or drag force. Typically the force acting normal to the rock surface, or the bit normal (thrust) force, is less than the drag force. However, as the bit becomes blunt and a wear flat forms at the tip (Figure 1b) the bit normal force increases very rapidly. A brief discussion of the cutting tools, area of application, cutter life and wear issues, and selection criteria is offered by different researchers [5, 6, 7].

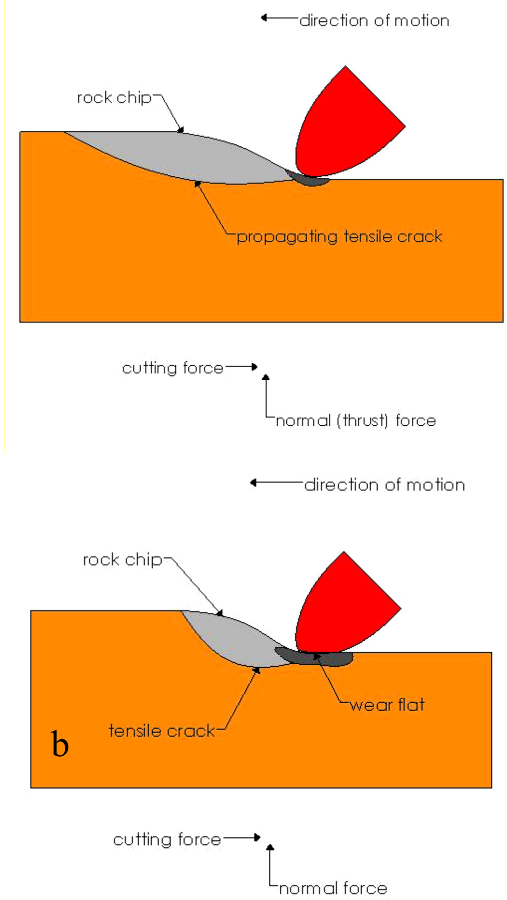

Figure 1. Cutting action of (up) sharp and (b) blunt drag bit

An indenter is a tool that breaks the rock when it is pressed normally against a rock surface (Figure 2). As the bit is forced to the rock surface, a pressure bubble or crushed zone is formed under the contact area. Interestingly, this pressure bubble causes the rock to fail primarily by creating tensile cracks as it expands laterally. When the load on the tool is sufficiently high to generate enough pressure in the crushed zone, some of these cracks propagate to the surface and form rock chips. Same principal is used when the roller cutter i.e. a disc cutter rolls over the rock or when a multi row cutter pushes the carbide inserts into the rock surface.

The description of the rock failure process for these two types of cutting tool applies only to rocks that respond to load in an elastic-brittle manner. Brittle materials are weakest in tension – hence easier to cut with both tool types. These materials are strongest when they are loaded in confined compression, exactly the loading situation that exists beneath an indenter – hence there is a need to apply very high tool forces to cause rock failure, meaning the need for high thrust force.

It can be concluded that drag bits are more efficient cutting tools than indenters, that is, they require less force (energy) [7, 8]. Unfortunately, drag bits are much more susceptible to wear and failure than indenters, consequently their use is limited to cutting weak, and generally, non-abrasive, rock materials. Drag bits are practically inapplicable in harder more abrasive rocks since their life is too short and the machine down time for cutter change is too much to allow for any reasonable cutting/production time.

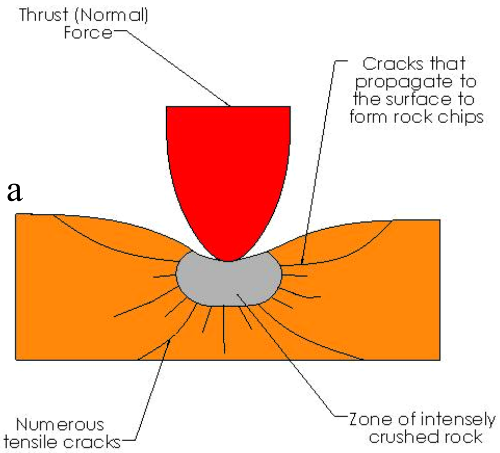

Figure 2. Breakage action of indenter

3. Pertinent rock parameters

The main rock characteristics related to rock fragmentation are tensile and shear strength of rock. These parameters, which are typically depicted by measurements made in the laboratory on core samples, indicate the resistance of rock to disintegration. Another important factor in rock fragmentation is brittleness of material, represented by the ease of developing a crack when certain thresholds of stresses are exceeded. The opposite of brittleness is a material that is perfectly plastic (ductile) and it reached the point of peak stress, continue to deform with no additional load, and no crack will develop in the material by the induced stresses.

The relevance of brittleness to cutting is that a perfectly plastic (ductile) material cannot be broken by an indenter because, as illustrated in Figure 3a, loading this material simply plastically deforms it without producing any cracks. Perfectly plastic materials can be cut by drag bits. However, because ductile materials are weaker in shear than they are in tension, the failure mechanism is one of shear (Figure 3b). Metal cutting typically uses a drag bit to machine a plastic material.

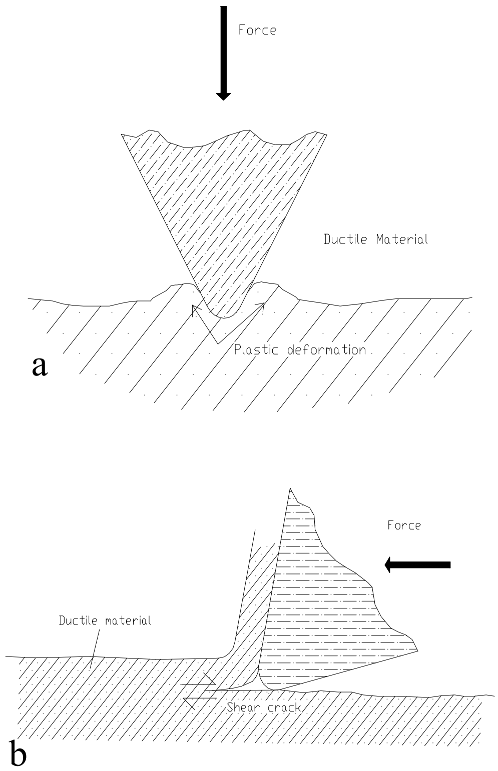

Figure 3. Cutting ductile material by (a) an indenter and (b) a drag bit

Unlike plasticity, the abrasivity of a rock does not affect whether or not it can be cut. It does, however, determine whether or not the rock cutting operation can be performed economically. Very high rates of cutter wear can result if the rock abrasivity is too high or the cutting methodology too severe. Rabinowicz identified four mechanisms for the wear of materials [9]: adhesive wear, abrasive wear, corrosive wear, and surface fatigue wear. Generally, for rock cutting tools, the most damaging of these is abrasive wear [7, 8]. This occurs when a hard rough surface slides against and plows grooves in a softer surface. In principle this should not pose a problem since the room temperature hardness of rock cutting tools– whether they are manufactured from hardened steel, cemented tungsten carbide, or polycrystalline diamond– is generally considerably greater than the room temperature hardness of the hard minerals commonly found in rock. In practice abrasive wear of rock cutting tools is a significant problem because all materials soften with heating and the frictional heating that takes place beneath the cutting tool causes the tools made from steel and tungsten carbide to soften more rapidly than the common hard minerals – such as quartz and corundum – found in rocks. At some critical temperature, typically 400-500 degrees Celsius, the particles of crushed rock (illustrated in Figures 1 and 2) become harder than the tool materials and they then plow grooves in and abrade the softer tool material.

This phenomenon typically limits the use of drag bits in rock cutting [8]. During the cutting operation the same part (tip and wear flat) of the drag bit remains in constant contact with the rock, which is constantly moving and fresh surfaces are exposed. When the cutting conditions become difficult, that is when the rock becomes stronger or more abrasive, tool life can be enhanced by reducing the tool velocity through the rock. This reduces the frictional heating but, of course, it also reduces the rate of rock excavation. When cutting stronger and more abrasive rocks with drag bit machines a practical way of maintaining acceptable excavation rates whilst maximising bit life is to increase the cut depth but use relatively low tool speed through the rock. Another factor to consider is that cutting tool materials respond, like rock, to load in an elastic-brittle manner. Consequently these tool materials, like the rock, are susceptible to brittle failure.

An inherent advantage of rolling (indentor) cutters, such as disc cutters or tricone bits, is that the heat load generated at the rock-tool interface is distributed around the cutter circumference rather than being concentrated in a limited fixed area, as is the case with a drag bit. Another advantage of rolling type cutter is that the load applied is compressive; hence the brittle elements of the cutting tool materials far less susceptible to brittle failure. As noted above, this compressive loading is a mixed blessing because it makes the rock breakage process inherently inefficient, meaning that very high cutter forces are required to affect breakage. The consequence of these high forces is that very large machines are required to re-act them.

4. Recent innovations in rock excavation

Many attempts have been made for decades, so far unsuccessfully, to develop mechanical excavation systems for hard rock mines. Some of the concepts have progressed to field trials and prototype machines generally were capable of excavating very hard, and often abrasive, rocks. But almost all of these machines have failed due to the short life of the cutting tools which reduces the production time (machine utilization) and makes the application uneconomic. The real battle is the abrasion wear of the cutting tools when drag type tools are used on partial face machines. Partial face machines have the mobility and flexibility needed in mining application to excavate various opening shapes, be able to move around from face to face, and make right angle turns. Yet, due to the lack of rigidity in the system, available forces for rock cutting in partial face machines is limited and thus precluding them from using roller type cutters for use in harder rock. In reality the production rate of many of these machines have been less than that achieved by conventional drill-and-blast method, often because of the downtime associated with changing cutters. Thus the focus of the research in this area has been to develop cutting tools that require low cutting forces when cutting hard rock formations. This allows them to be used in combination with partial face machines for the desired operational characteristics. Following is a brief discussion of new and emerging rock cutting tools.

4.1. Undercutting discs

One of the most interesting new developments in rock cutting has been to use a modified version of the robust disc cutters (developed for use on boring machines) to attack the rock in an undercutting manner, similar to the cutting action of a drag bit (Figure 4). Because this cutting action generates tensile stresses in the rock much more directly than the standard, indentation action of a disc cutter on a boring machine, it is far more efficient, meaning that the force required to break the rock is much lower.

The theoretical benefit of reduced disc cutter forces when undercutting the rock has been

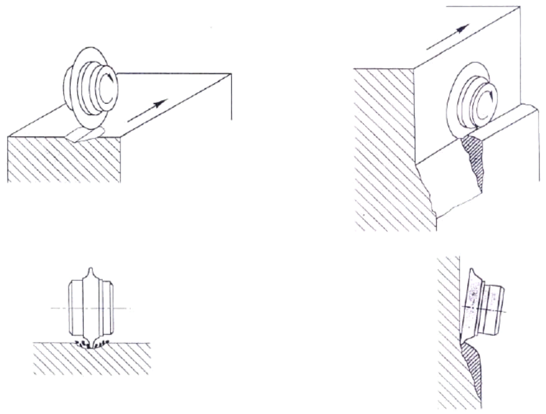

Figure 4. Conventional disc cutter (left) versus undercutting disc (right)

verified in CRC Mining's research laboratories in Brisbane, Australia. A large number of tests have been conducted in numerous different rock types. The results from experiments carried out cutting in 36 MPa sandstone given in Table 1 illustrate the point. In these experiments a small disc cutter, 50 mm in diameter was used to machine grooves 10 mm deep with 30 mm spacing between adjacent grooves. It is apparent that both the normal (thrust) and the cutting (rolling) forces were reduced by a factor of about 2.5 when undercutting was employed.

Table 1. Comparison of disc cutter forces – conventional (indentation) cutting and undercutting

	Conventional Disc	Undercutting Disc
Normal (thrust) force (kN)	18	6.8
Cutting (rolling) force (kN)	4.5	1.8

The frictional contact between the disc cutter and the rock causes the cutter to rotate during the undercutting operation and, as noted above, this distributes the heat load around the circumference of the disc keeping the cutter far cooler than an equivalent drag bit, therefore preserving the tool sharpness. It does not overcome the problem of introducing potentially dangerous bending stresses in the brittle steel discs during the cutting operation and this could limit the strength of rock that could be machined using this approach. Two manufacturers, Wirth and Voest Alpine, have developed machines based on this concept and they were put to field testing in underground operation.

4.1.1. Wirth Machines

CMM-MTM

In the late 1980s the German equipment manufacturer, Wirth entered into a joint research program with the Canadian consortium HDRK to develop a continuous mining machine for excavating hard rock (Figure 5). The concept developed was based on undercutting discs. The initial testing of this concept used a modified Atlas Copco mini full facer to cut sandstone in a quarry. These trials were sufficiently encouraging that a new machine, termed by HDRK as the CMM (or continuous mining machine), was designed and constructed. This machine had four arms, with an undercutting 560 mm diameter disc cutter mounted at the end of each arm. The motion of the cutting arms was programmable to cut a variety of shapes of tunnel cross section. The machine was designed for each cutter to experience a mean thrust force of 250 kN and a peak thrust force of 1 MN. The power provided to the cutting head was 525 kW and the total machine power was 700 kW [10]. The machine, which weighed 150 t, was capable of excavating a tunnel 4.25 m in diameter.

Figure 5. Wirth Continuous Mining Machine (CMM) [8]

Proof-of-concept testing of this machine was carried out in the same sandstone quarry in Germany in 1993 over a four month period. The rock had a uniaxial compressive strength (UCS) of 120-140 MPa and a uniaxial tensile strength (UTS) of 10-13 MPa [10]. In these quarry trials the CMM excavated at the respectable rate of 8-16 m^3/h/cutter.

The machine was then moved to a nickel mine in Canada, where the rock UCS was reported as 250 MPa and the UTS at 16 MPa [10]. An excavation was started but unfortunately these trials were prematurely curtailed after mining only some 200 m^3 of rock, when Inco withdrew from the HDRK joint venture. Hence the excavation potential of this machine in strong rock has never been properly evaluated.

In the conclusions of his paper Weber comments

that [10]:
- The thrust and gripper forces of an undercutting machine are much lower than for a conventional TBM.
- A machine using the undercutting principle needs only approximately 50% of the power and has only about 50% of the weight of a comparable conventional TBM.
- This can lead to lower capital costs, lower transport costs, and lower erection and launching costs than a TBM.

Wirth is still interested in marketing this machine which it has redesigned and re-named the Mobile Tunnelling Machine – MTM 550H. This machine weighs 135 t, has a total installed power of 800 kW and is capable of excavating a 5.6 m diameter circular tunnel or a 4.4 m square tunnel.

TBE 500/1440 H-HST

Much more recently (from 2003 to 2006) Wirth has used the undercutting disc approach to drive two 14.4 m diameter tunnels (the Uetliberg tunnels) for distances of several kilometres as part of the new Zurich western by-pass. The rock excavated was a combination of harder sandstone and weaker marl. The tunnelling process was carried out by first driving a 4.5 m diameter pilot tunnel with a conventional TBM in the centre of the excavation. This tunnel was then reamed to 14.4 m diameter using a machine that Wirth calls a Tunnel Boring Extender (TBE).

This machine's boring head had six cutter arms. The disc cutters are mounted on slides in these arms and the slides are drive radially outwards whilst the cutter head is rotated (Figure 6 left). The cutters therefore follow an increasing spiral pattern as they machine (undercut) the rock (Figure 6 down). This reaming machine is braced in the pilot tunnel (Figure 6 up) [12].

Wirth claims that this new approach to tunnelling requires less installed power than an equivalent conventional TBM and has only 50 % of the weight of a TBM. One of Wirth's competitors, Herrenknecht, provided conventional TBMs for this same project. They claim that the conventional machines were faster and did not require the extra step of driving a pilot tunnel. Wirth admits to experiencing learning/teething problems on the first of the two tunnels but claim the second tunnel proceeded better. They claim that the pilot tunnel is an advantage because it gives the contractor detailed geotechnical information ahead of the main excavation and it provides through ventilation, eliminating dust problems at the face.

Whatever, the merits of these arguments, the fact that a number of kilometres of tunnel have been successfully driven using the new technology of undercutting discs is an achievement. Also, the fact that the machine weight and power required for this approach to cutting is substantially less than that needed for a conventional TBM is potentially of significant interest to mining applications. Unfortunately the feasibility of using this cutting approach in strong rock has not yet been convincingly demonstrated by either of the Wirth machines.

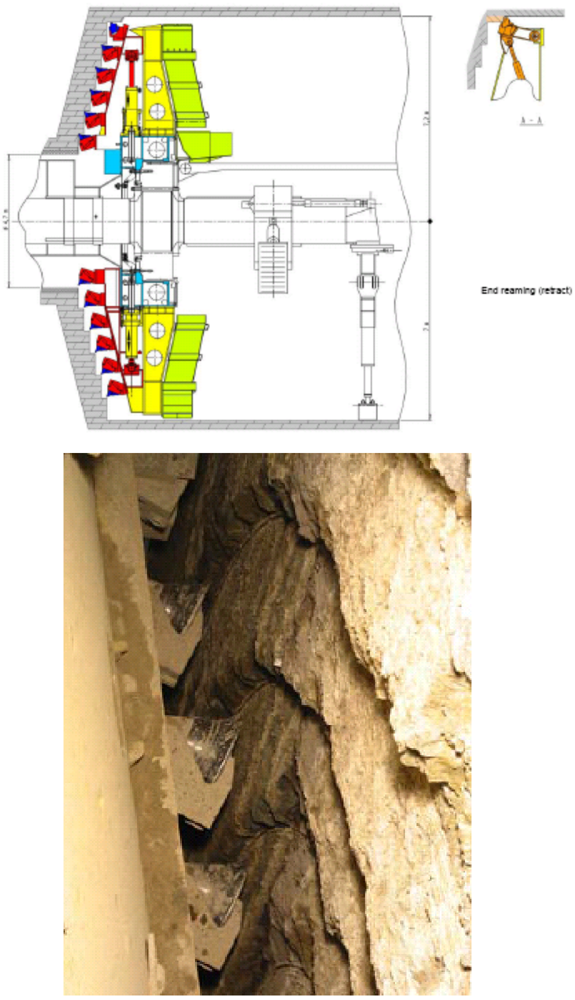

Figure 6. Wirth TBE 500 cutterhead (up) and Tunnel face and undercutting discs (down) [11]

Voest-Alpine Sandvik Reef Miner ARM-1100

Voest Alpine Sandvik of Austria has manufactured three of these machines and tested in the platinum mines in South Africa. The first, prototype machine, an ARM-1000, cut a 1 m high slot. The other two, both ARM-1100s, cut a 1.15 m high slot (Figure 7). These machines have been tested in the two main platinum reefs, Merensky and UG2. The Merensky is the stronger rock with typical UCS values of 150-200 MPa. The UG2 reef varies in strength typically from 40-120 MPa. Both rocks are highly abrasive but UG2 is even more abrasive than Merensky (UG2 is composed predominantly of the hard minerals chromite, plagioclase and clinopyroxene with Mohs hardness values of 5.5, 6 and 5-6, respectively).

Figure 7. The Voest Alpine Sandvik ARM 1100 [13]

The prototype machine performance was sufficiently encouraging that two companies, LonPlats and Implats, each ordered and tested an upgraded version, an ARM-1100. The LonPlats machine was initially trialled in the UG2 reef. Apparently it cut the rock successfully but the cutter costs were very high. Recently LonPlats has moved this machine into Merensky reef where, according to a Sandvik-Tamrock source, it is cutting at a higher rate than in the UG2. The machine cuts a slot 4.25 m wide. The targeted advance rate by the manufacturer was 1 m/h (or 4.25m x 1.15m x 1m = 4.89m^3/h = 20 t/h) and, according to this same source, this has been achieved, although not yet consistently. Another source claimed that the actual mining rate achieved with the ARM-1100 to date has been of the order of 2,500 t/month (about 625 m3/month). According to a mining company source a production mechanised excavation system will need to excavate at four times this rate, or 10,000 t/month.

The cutter costs continue to be a problem with this machine in these platinum reef applications. The Implats machine was deployed in Merensky reef. Problems were experienced with high levels of dust and the cutter costs were excessive. Seemingly this machine has been withdrawn from the mine. The reported cost of extracting the rock on the face using these machines has been 21-31 Euro per tonne of ore. This is equivalent to the total mining cost using conventional drill-and-blast methods. In order to be competitive this face stoping cost needs to be reduced to about five Euro per tonne. Clearly work remains to be done to achieve a consistent mining rate at an acceptable cost [14].

In summary, these three machines have excavated some 6,000 m^3 of rock. The machines appear to have performed marginally satisfactorily in difficult, highly abrasive rock conditions. Sandvik-Tamrock is working to improve cutter performance and to achieve consistency of machine advance rate. One of the two mining companies that trialled this technology still has faith in it and they are continuing to work with the manufacturer to improve it.

4.2. Activated/Oscillating Disc Cutting

Over the past decade, work has been undertaken by different groups using a disc cutter which oscillates in a plane orthogonal to the disc axis whilst it attacks the rock in an undercutting manner (Figure 8).

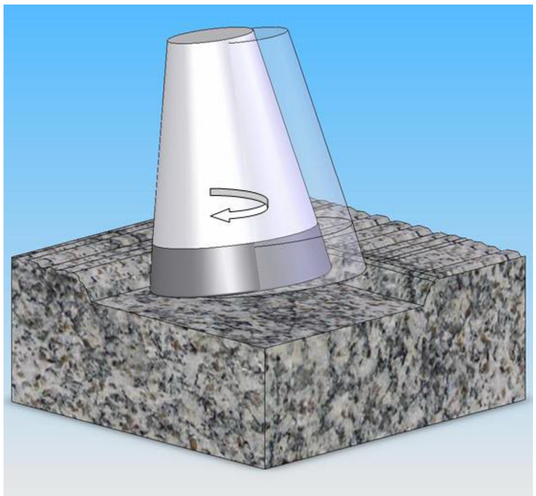

Figure 8. Undercutting and oscillating (activated) disc cutter

The reasoning behind adding the complication of this oscillating cutting action is that cyclic loading of rock can induce fatigue cracking in, and therefore weakening of, the rock.

The effect can be dramatic as shown by results of cutting tests in sandstone. Table 1 is the summary of test results with oscillating cutter at a frequency of 35 Hz. The results, given in Table 2, make it clear that oscillating the disc cutter reduced the normal (thrust) force on the undercutting disc by a factor of 3.8 (1.8 kN compared with 6.8 kN) and reduced the cutting force on an undercutting disc by a factor of 1.5 (1.2 kN compared with 1.8 kN). The cutting forces on the undercutting oscillating

Table 2. Comparison of disc cutter forces – conventional (indentation) cutting, undercutting with no oscillation, and undercutting whilst oscillating at 35 Hz [16]

Oscillating Frequency	0 Hz Conventional Disc	0 Hz Undercutting Disc	35 Hz Undercutting Disc
Normal (thrust) force (kN)	18	6.8	1.8
Cutting (rolling) force (kN)	4.5	1.8	1.2

disc was 10 and 3.75 times lower than on the conventional disc for normal and rolling forces, respectively [15].

A more comprehensive suite of tests illustrated this point further. In these tests a disc cutter was used in an undercutting mode to machine a groove in a marble with a uniaxial compressive strength of 90 MPa. In the left-hand plot in Figure 9 the measured forces with zero oscillation are given in the upper curve – mean cutting force of about 30 kN and mean peak cutting force of about 38 kN. (the under cutting process similar to Wirth and Voest-Alpine machines). When an equivalent cut was made in the same rock with the same cutter at the same cut depth and cutting velocity the mean force was reduced to about 7 kN and the mean peak force to about 9 kN (bottom curve). The decrease in cutting force with increasing frequency of cutter oscillation is shown in the right-hand plot in Figure 9. These two figures show clearly the benefits of oscillating the cutter.

One of the first people to recognise the potential benefit of cyclically loading the rock with an undercutting disc cutter was a German worker, Ulrich Bechem, who filed a patent describing a mechanism on how to 'activate' a disc cutter in 1988 (US patent: 5190353). This early work has been followed by subsequent patents. Mr Bechem has worked with several companies to try and commercialise this novel 'activated' cutting approach.

Most recently this activated disc cutting approach has been conducted by the German mining machinery company DBT working in partnership with Anglo Platinum in South Africa. The first underground trial of this partnership was conducted in 1999 in a platinum mine excavating the UG2 reef. A series of trials has been carried out on the same stope face from then until today and this work is ongoing. An impartial assessment of the progress to date the performance of the system has been abysmal. According to an Anglo Platinum spokesperson the cumulative advance from these trials in this approximately 30 m long, 1 m high stope, has been 1 m or less. Two problems have dominated. One, as expected, has been poor life of the cutters. The other has been repeated failures of the drive mechanism that causes the cutters to oscillate (or activate). This activation mechanism requires the use of an eccentric shaft mounted in housing with rolling and thrust bearings and, crucially, a gearbox.

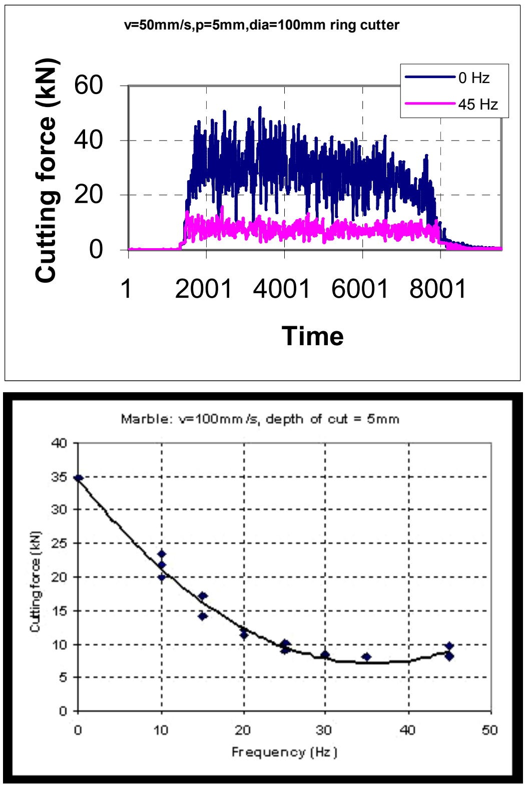

Figure 9. Measured disc cutting forces in marble showing the influence of cutter oscillation [16]

Apparently the gearbox has been a constant source of problems and the bearings have also caused difficulty. DBT has recently completely redesigned the gearbox and the drive. These new components have been installed in the first Quarter of 2007 and further tests have been performed later on. The disc cutters used initially wore at an excessive rate, but further modifications have been undertaken.

The concept of oscillating a disc cutter to reduce cutter forces was developed independently by Mr David Sugden in Tasmania, Australia. Mr Sugden tested and patented to concept of what he called an '*oscillating*' disc cutter as early as 1970. Mr Sugden's patent was assigned to the Robbins Company of Seattle, USA, and the prototype for laboratory testing, was fabricated in Tasmanian

and later transported to Seattle, USA. No further action was taken to develop the technology at that time.
The technology was revived in 1996 when Dave Sugden introduced the technology to CRC Mining (formerly known as CMTE). Oscillating Disc Cutting (ODC) has some similarities to, but differs from the Bechem Activated Disc Cutting in several important respects. The technologies are similar in that both use disc cutters to undercut the rock whilst the cutter is oscillated. One important difference is in the drive mechanisms to achieve this oscillatory action. The ODC system does not use a gearbox and it has a much simpler, and more robust, bearing arrangement. Another difference is that the ODC employs an inertial mass between the cutters and the body of the excavation machine to dampen the magnitude of the, already reduced, cutter forces that are transmitted back to this machine. Furthermore, the ODC uses a series of high pressure water jets directed at the cutter-rock interface during the cutting operation. These jets serve two purposes. One, they further reduce the forces experienced by the cutter during the cutting operation. Two, they provide very direct cooling to the cutter, thereby preserving the hardness and life of the cutting elements [15, 16].
CRCMining/CMTE, has continued to develop prototype machine using the ODC technology, first for testing in the laboratory and later in a quarry. The ODC technology has been licensed for use in underground mining operations worldwide to Joy. The initial project that CRCMining was working on with Joy is to develop an underground mining system for use in the narrow reef mines in South Africa, particularly the platinum mines. A prototype system has been built in South Africa and field tested. This new mining system will be a competitor to the Voest-Alpine Sandvik and DBT systems.

4.3. Minidiscs

For disc cutting, the force requirements of the cutter to achieve a given depth of penetration are directly proportional to the contact area that the disc makes with the rock. This means for the same depth of penetration, a smaller disc size requires lower force to penetrate a given distance into the rock. Alternatively, a smaller cutter will penetrate deeper into the rock at the same thrust load. An argument can be made, therefore, that a small diameter cutter can be utilized either to drastically reduce machine thrust, torque or power requirements or to increase the attainable penetration rates in comparison to larger sized discs [17].
The Colorado School of Mines began its mini-disc development early 1990. The cutter initially developed at CSM was 5 inches in diameter and cantilevered on a pedestal mount (Figure 10).

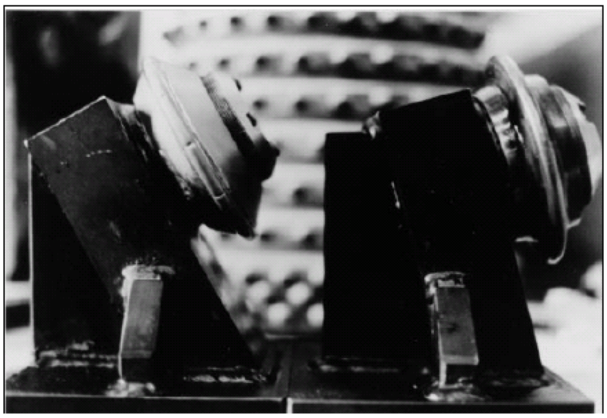

Figure 10. Prototype of 5 inches mini disc

The mini disc cutter has been subjected to extensive full-scale testing in a variety of soft and very hard, abrasive rock types [18, 19, 20, 21]. These tests were designed to evaluate its applicability on various types of mechanical excavators with a major emphasis on microtunnelling machines and small-diameter boring machines. Mini discs have advantages including: high cutting efficiency, high penetration rates, low cutting force requirements and thus lower machine thrust, torque, and power, low initial cost, low replacement cost, low maintenance costs, ease of replacement, elimination of the need for a cutter shop, true-rolling feature (meaning reduced torque and power requirements compared to button or multi-kerf cutters), greater lifetime and drive lengths compared to carbide cutters, and significantly reduced fines, meaning less slurry clean-up requirements [18, 19, 20, 21]. Key weaknesses of mini discs with pedestal mounting system were the sealing and bearing assembly, the cutter retaining system. In addition, the small size of the disc meant that it did not have sufficient wear material so that even small amounts of wear caused the blade to become blunt or shear off. This combination of problems brought an end to the pedestal mounted mini disc cutting program. The only mini-discs in use today are saddle mount discs from Robbins in the 6-10 inch range. These discs have been used in many of the commercially available machines manufactured by the Robbins Company, the mini Bore series tunnelling and microtunneling machines. There are still possibilities for using concept of minidisc cutters on partial face machines for mining application.

CSIRO's SMART*CUT technology

Polycrystalline diamond composites (PCD) materials are used extensively in the gas and petroleum industry. However, these composites are limited to temperatures less than 750 degrees. At temperatures greater than 750 degrees Centigrade, cobalt, the binder in the composite material, acts as a catalyst for the conversion of diamond to graphite. It should be noted that measured temperatures at the rock tool interface cutting hard rock cutting with drag bits can exceed 1,300 degrees Centigrade [22].

Super Material Abrasive Resistant Tools or SMART*CUT technology uses thermally stable diamond composites (TSDC) in the design and manufacture of cutting tools for mining, civil construction and manufacturing. TSDC overcomes the thermal instabilities limiting traditional diamond composites because it does not contain cobalt; however it posed a vexing bonding problem. In the past it has proven difficult to bond TSDC to cutting tools. CSIRO has developed and patented a bonding process that has enabled the assembly of rock cutting tools with TSDC [22, 23]. TSDC materials are claimed to be far more resistant to abrasive wear than tungsten carbide. Figure 11 illustrates the greater wear resistance of TSDC tools. It shows the tungsten carbide picks comparing with TSDC picks before and after cutting tests in sandstone (UCS=114MPa). CSIRO claims that these tools have been used to cut rocks with strengths (UCS) up to 260 MPa.

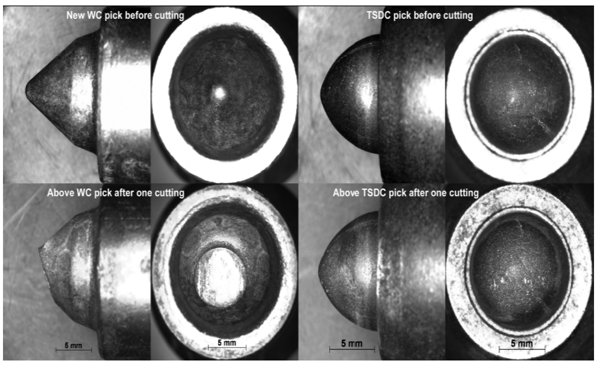

Figure 11. Tungsten carbide picks versus TSDC picks before and after test on sandstone (UCS 114MPa) [24]

According to Cunningham researches [22] costs for TSDC tools are expected to be two to three times that of a standard diamond carbide. This figure is probably far too low; TSDC cutting tools are likely to cost much more than this. Laboratory drilling trials have demonstrated that these prototype bits have twice the penetration rate and expend half the energy of traditional rock coring bits [25].

5. Conclusions

A great deal of work has been done by mining companies, machine manufacturers, and researchers on development of a flexible hard rock excavation system over the past couple of decades, with little to show for. This indicates the difficultly of such proposition. Surely there is still a strong market demand for these systems, exacerbated by shortage of skilled labour in underground construction and mining. It is by realistic optimism to state that there are technologies that have demonstrated great potential and promise for developing such machines. Full scale commercial production of these machines could happen in near future.

There is unlikely to be a quick, or even a single, solution to this challenge and, if a solution were to be proven in full scale production, it requires not just persistence but also significant funding. The stake holders, including mining companies need to work hand-in-hand with manufacturers and receive reasonable support by academic institutions as well as government research funds to overcome this challenge. All parties need to realise that, whichever approach is taken, will not succeed immediately and a joint vision and commitment along with concerted efforts should be established to conduct the required multi-year development program and achieve the intended goals.

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