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Advances in Hard Rock Cutting Technologies An Overview

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Abstract

In this paper, a brief review of rock cutting principles and the cutting technologies for hard rock excavation has been carried out with a view to address the need for a better technology for hard rock excavation. The recent technology of oscillating disc cutting is described and the advantages over other cutting systems are highlighted. Comparison is made of the test results with that of the conventional disc cutting technique employed in most tunnel-boring machines. Experimental results clearly indicated the advantages of the new cutting technology in the construction of a lightweight flexible machine for hard rock excavation.

Introduction

The advantages of rock excavation by mechanical tools, over conventional drilling and blasting methods, in terms of ground vibration, support requirements, safety, automation, dilution control and contour excavation has been realized over the years.

The technology for the mechanical excavation of low to medium strength rock has been substantially well developed, and therefore it has been used as an alternative technology to drill and blast excavation (Gertsch, 1994). However, in the case of hard rock excavation, especially for mining excavations, such advancement in the development of an efficient and effective cutting system has not yet been achieved. This is partly because of inadequate understanding of the basic mechanism of rock cutting and partly because of a lack of understanding in the fundamental processes involved in the rock cutting machines. A better understanding of these fundamental processes will enable the development of a more scientific approach for the design of cutterheads for hard rock excavation.

In this paper a brief review of the advancements made in hard rock cutting technologies has been undertaken.

Cutting Principles

The most commonly used tools for rock cutting are drag bits (or picks), button cutters and roller disc cutters. These tools are laced in a designed pattern on the cutterheads of the excavation machines to enable either full face or partial face rock excavation. All these tools can be classified into two types: drag bit and indenter.

A drag bit cuts the rock by undercutting and frictional drag with a tool motion parallel to the rock surface. Figure 1 illustrates the cutting principle of a drag bit. Most of the drag bits are either chisel (wedge) or conic in shape. The drag bit produces a high stress concentration in the rock adjacent to the bit, causing distinct fractures to propagate in the rock away from it. Machines that use drag bit cutting include longwall shearers, roadheaders and continuous miners. Efforts are being made to extend the range of rocks that can be economically machined with drag bits by developing wear-resistant materials

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(such as polycrystalline diamond). Another approach has been to assist the rock cutting operation by using high-pressure water jets (Hood, 1976 and 1977). Although harder tool materials and water jets can extend the range of rocks that can be machined with drag bits, these tools remain limited to applications in weak to medium strength rocks.

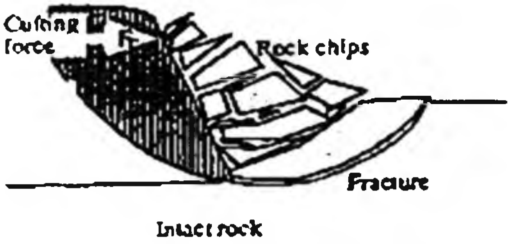

Fig. 1: Drag bit cutting principle, after Whittaker *et al.* (1992)

An indenter breaks the rock in compression with a tool motion perpendicular to the rock surface (Fig. 2). The rock beneath the indenter is crushed under high stress. The crushed zone dilates causing tensile cracks to initiate and propagate through the rock. The indentation process is energy intensive because most of the applied energy (about 85–95%) is spent in rock crushing rather than in chip formation. These tools are therefore less energy efficient than drag bits. Machines that use indentation as the cutting principle include Tunnel Boring Machines (TBMs), mobile miners, raise and shaft borers, and most drills. Commonly used indenters include button cutters and roller discs cutters (U-shaped cross section). Although indentation breakage of rock is energy intensive and produces fines, this principle is popularly used for hard rock excavation. This is mainly because tool wear is lower in the cutting operations (since there is no tool dragging). The efficiency of indentation is improved when multiple indenters are used because large chips are produced between the cutters.

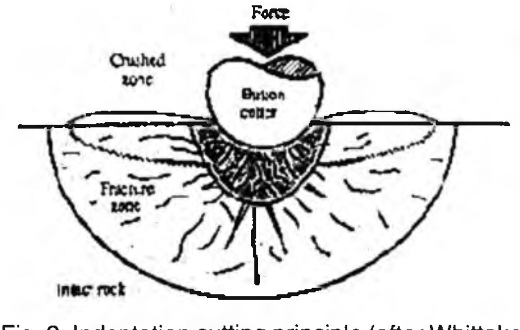

Fig. 2: Indentation cutting principle (after Whittaker and Frith, 1990)

Developments in Hard Rock Excavation Machines

Two types of machines commonly used for hard rock excavation are full-face and partial-face machines. In the case of full-face machine, the size of the cutterhead is almost the same size as that of tunnel face (eg. tunnel boring machine). While in a partial-face machine, the cutterhead is smaller than the cut section and it excavates by sweeping the cutterhead across the rock face (eg. roadheader). A brief review has been carried out on full-face and partial-face hard rock cutting machines that have been developed in the past one or two decades.

Full-Face Tunnel Boring Machine

The majority of hard rock excavations (for civil engineering tunnels) are carried out by large-scale full-face tunnel boring machines (TBMs). These typically use free rolling disc cutters. These cutters break rock in compression by the energy intensive indentation principle. TBMs require large

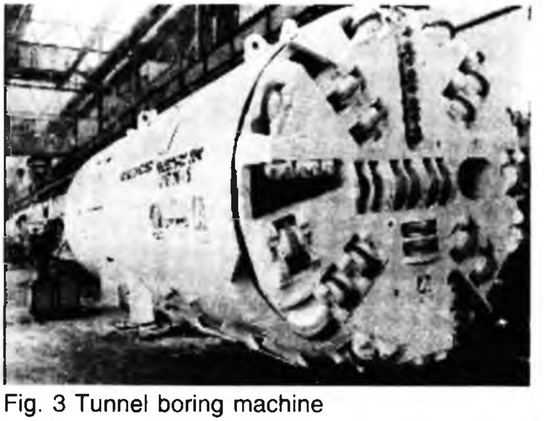

Fig. 3 Tunnel boring machine

forces to machine the entire face. The large thrust force is supported by the machines massive structure with large traction cylinders (Fig. 3). Consequently, a TBM is inflexible (difficult to change direction) and expensive. These constraints make it difficult to achieve the desired excavation shapes for mining applications. A few TBMs use a hybrid method of cutting employing both disc cutters and drag bits on their cutting head. In this hybrid method, the rock between the disc cutters undergoes cracking, and the drag bits that are located between these disc cutters removing the cracked rock material.

Partial-Face Mobile Miner

A recent advancement in hard rock excavation for mining has been in the development of a partial-face cutting machine, such as the Robbin's Pasminco Mobile Miner with free rolling disc cutters (Fig. 4). In this configuration the cutter forces are concentrated on the partial face rather than a full face, and therefore do not offer the same high reaction force as that of a TBM and hence do not require a huge structural mass (unlike full-face cutting machines). These machines are comparatively more flexible by virtue of their smaller machine size. However, the cutters still break the rock in compression using the indentation principle and most of the energy is expended in crushing the rock rather than in chip formation. In this machine, unlike the TBM, the disc cutters do not track in the same grooves. As a result, individual cutters experience a higher force in the subsequent sweep (Guan, 1997). In addition, as the cutting wheel sweeps across the face the cutters follow a spiral path from the top to the bottom of the face, causing each cutter to cut with a skew angle; this results in large bending forces on the discs, causing excessive disc wear and premature failure of the cutters (Guan, 1997).

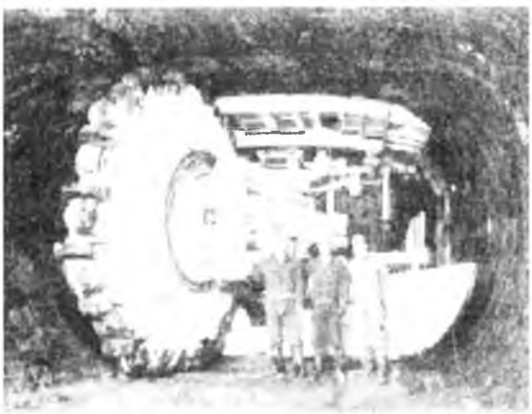

Fig. 4: Mobile Miner used in a zinc mine at Mt. Isa Mines, Australia (Guan, 1997)

Drum-based Mini-Disc Cutter

Another fairly recent development for hard rock selective mining has been a drum-based cutterhead laced with a number of rolling mini-discs as shown in Figure 5. These mini-discs (5 inch diameter) require less thrust and power to break the rock, and therefore these machines are more mobile than, say, TBMs. The concept of using mini-disc technology for hard rock excavation was originally advocated by the Colorado School of Mines

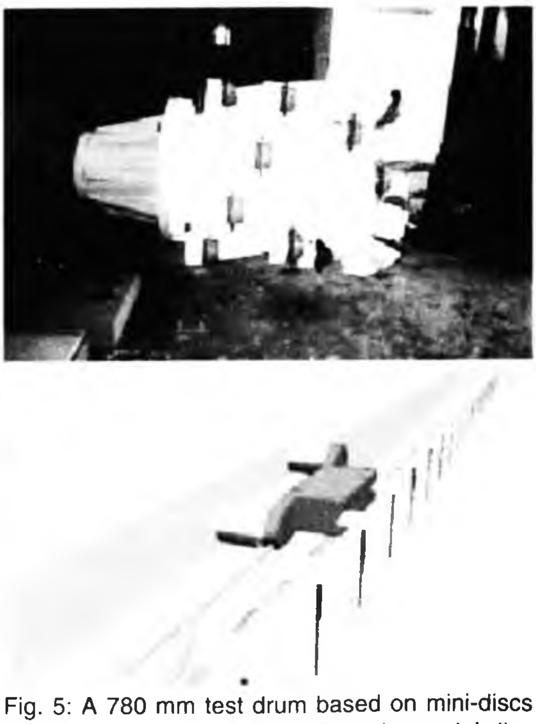

Fig. 5: A 780 mm test drum based on mini-discs (left), and a mining system based on mini-disc drums (right) (after Willis *et al.*, 2001)

and Excavation Engineering Associates, Inc., USA. The Council for Scientific and Industrial Research (CSIR) in South Africa recognised the potential of these mini-disc cutters in a long or short wall application for selective hard rock mining in 1999, and trials are being carried out in a platinum mine. The efficacy of the cutting technique in this application has yet to be proved. Although mini-disc cutters require less force than large discs, they still use the indentation principle to break the rock—an energy intensive technique. A problem that still needs to be addressed in these drum-based cutters is the development of small bearings and mounting structures to withstand high loads caused by the indentation cutting principle (Willis *et al.*, 2001).

Undercutting Technology

Clearly, a way to reduce tool forces is to break the brittle rock by exploiting its weaker tensile strength. This can be done by undercutting. In undercutting, the disc cutter penetrates the rock to a prescribed depth of cut with its plane almost parallel to the cutting surface, enabling the fracturing of rock predominantly by tension. The cutting process is less energy intensive compared with the indentation cutting used in TBMs.

HDRK-Wirth Continuous Mining Machine

In an effort to build an efficient rock cutting machine, HDRK Mining Research (Canada) and Wirth (Germany), developed a HDRK-Wirth Continuous Mining Machine for hard rock excavation. This machine used rolling disc cutters to undercut the rock. The undercutting mechanism exploits the weaker tensile strength of the rock, and the crack propagates towards its free surface with substantially larger fragments. The energy spent in rock crushing and chipping in undercutting mode is less than that of the indentation breakage mode. The HDRK-Wirth machine incorporated four cantilever-mounted cutters to allow flexibility and proper spacing

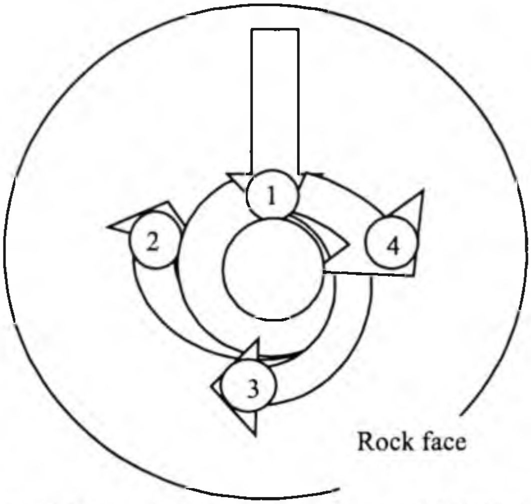

Fig. 6 The rock cutting pattern in the HDRK-Wirth continuous mining machine; cutter-1 causes depression and the rest work at the same arm diameter in spiral cutting tracks

of the cutters. In this machine, the first cutter creates a depression in the middle of the face by being swung from outside towards the centre (Fig. 6). This is followed by undercutting sweeping by the remaining three cutters from this depression to the outer periphery in spiral cutting tracks (Fig. 6). When the three discs reach the maximum inner circular profile of the tunnel cross-section, they begin to form the corners as required. Unfortunately the HDRK consortium was disbanded during early trials and hence this concept remains largely unproven (Hood and Alehossein, 2000).

Activated Roller Disc Cutter

A new cutting technology called activated cutting was developed and patented by Mr. Bechem in Germany under U.S. Patent No. 3860292 in 1975. CSIR-Mining Tek, South Africa, collaborated with Mr. Bechem, and experimented with this novel technology for hard rock excavation. The concept involved superimposition of vibrating forces on the cutting action. The cutter activation was achieved by using an eccentric shaft to create the oscillations and a counterweight to balance the unbalanced loads, as shown in Fig. 7 (Willis *et al.*, 1998). In this method the static thrust required is smaller as rock is disintegrated by impact pulses of the activation system. However, the mechanical problems in generating sufficiently high dynamic forces at a higher frequency have severely limited the use of activated cutters in hard rock (Fęnn, 1985). Nevertheless, they have achieved some success in cutting medium strength rock. The typical mining concept for the activated cutter system is shown in Fig. 7. This cutting system is being trialled in a medium strength chromite rock type in a platinum mine in South Africa.

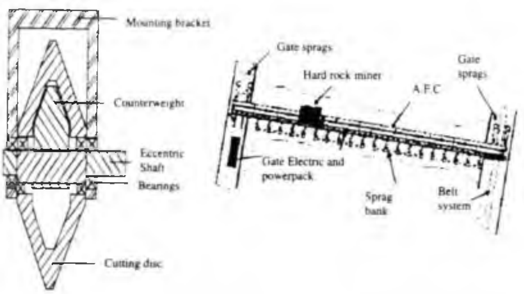

Fig. 7: Principles of activated cutting methods: eccentric shaft creates a counterweight to balance the unbalanced loads (left); a mining concept for activated cutter system (right) (after Valicek *et al.*, 2001)

Sandvik Tamrock Voest Alpine Rock Cutting Technology

A similar undercutting rock excavation technology for narrow reef mining is being developed by Sandvik Tamrock Voest Alpine (Fig. 8). In this technology, the undercutting concept utilises a free rolling large disc cutter (300 mm diameter). The prototype narrow reef miner of Sandvik Tamrock Voest Alpine is being tested in one of Lonmin Platinum's mines in South Africa.

Oscillating Disc Cutting Technology

In parallel with these overseas trials, a major project has been undertaken by a research team at the Cooperative Research Centre for Mining Technology and Equipment (CMTE) in Australia to develop a novel technology termed oscillating disc cutting (ODC) for hard rock excavation. The purpose of the project was to develop a system capable of excavating strong, abrasive rock at high rates, low cost, and with low forces transmitted back to the body of the excavation machine.

Cutting principle

The oscillating disc cutting concept was originally conceived by Mr. David Sugden (an Australian mechanical engineer), and the concept is described in Australian Patent No. 466,244 and U.S. Patent No. 3,554,604, 1971. The cutting concept of ODC is illustrated schematically in Fig. 9. It is similar in some respects to the activated cutter, i.e., superimposition of vibrating forces on the rock cutting action. However, it uses a different approach to cause the cutter to oscillate and

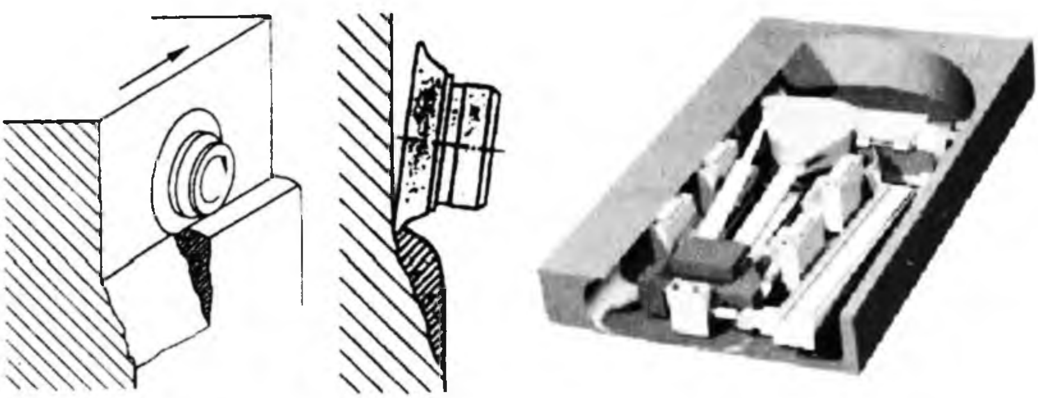

Fig. 8: The undercutting mode adopted in disc cutting (left); the conceptual model of Narrow Reef Miner (right) (after Pickering and Ebner, 2001)

it employs an inertial mass (mounted between the cutter and the excavation machine) to dampen the peak cutting forces that are transmitted to the structure of excavation machine (Karekal, 2003).

The ODC employs a free-rolling disc cutter, which cuts the rock in undercutting mode. Since this failure mode requires stresses that are an order of magnitude lower than for compression, the ODC does not require massive support to provide the reaction forces. A function of the free-rolling disc is to minimise the cutter wear during cutting operation. The disc is oscillated at a small amplitude (1.5–2.5 mm) by an internal hydraulic drive (similar to the motion of an orbital disc sander). This facilitates the process of crack initiation and propagation in the rock by repeated loading and unloading. Moderate pressure (<100 MPa) water jets are directed at the cutter-rock interface. These provide direct cooling to the tool, thereby enhancing cutter life. They also serve to continuously flush out crushed rock from beneath the tool, allowing the cutter to interact directly with, and to initiate and propagate, cracks in the intact rock.

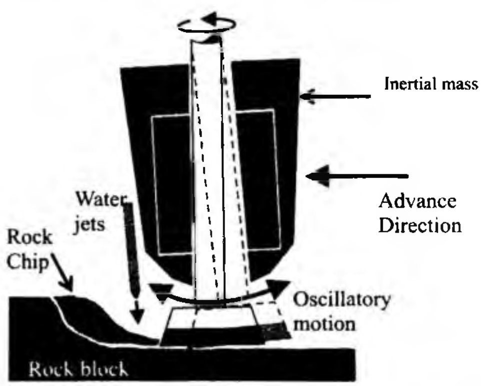

Fig. 9: Schematic representation of oscillating disc cutter operation in undercutting mode

Comparison with conventional disc cutter

The performance of the ODC has been compared with a conventional disc cutter. Fig. 10 shows the force acting on a conventional disc cutter machining a groove 35 mm wide, 15 mm deep in a block of Harcourt granite—uniaxial compressive strength of 160 MPa. Figure 11 shows the force acting on the oscillating disc cutter machining a groove 55 mm wide, at the same 15 mm cut depth, in the same rock when the disc cutter is oscillated at 45 Hz. It is apparent that the force required to excavate the rock is 550 kN with the conventional cutter and only 12 kN with the ODC. These plots (Figures 10 and 11) indicate the effectiveness of the undercutting technology adopted in ODC to exploit the weaker tensile strength of rock when compared to indentation breaking of rock as in conventional roller disc cutters.

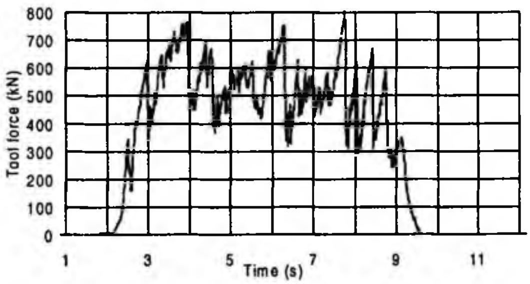

Fig. 10: Thrust force distribution in conventional disc cutter. (Steel cutter 311 mm diameter; cutting speed 100 mm/sec; penetration 15 mm; groove width 35 mm); after Hood et al., 1998

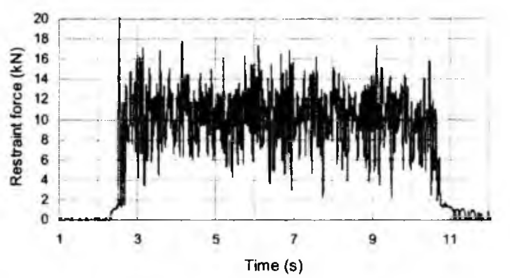

Fig. 11: Restraint force distribution in ODC for Harcourt granite (WC 50 mm disc cutter; oscillating frequency 45 Hz; cutting speed 100 mm/sec; depth of cut 15 mm; groove width 55 mm)

Summary

A brief review of rock cutting principles and the cutting technologies for hard rock excavation has been undertaken. Although the existing technologies have some merits and demerits, to be viable for hard rock excavation they still have to demonstrate they are efficient and economical. This has been partly attributed to inadequate understanding of hard rock breakage in relation to the combined interaction of tool-rock and machine, and partly due to a lack of advancement in the development of high strength wear resistive tool materials. Although it has been realised that mechanisation through automation of mining operations is the key to the success of future mining, the mining industry is still striving to meet the challenge to build an economically viable and efficient rock breaking technology for hard rocks. Any advancement towards achieving this goal will have large benefits to the mining industry in terms of productivity and the health and safety of the workforce.

Acknowledgement

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