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A REVIEW OF EXPLOSIVE-FREE ROCK BREAKAGE (EFRB) TECHNOLOGIES IN MINING INDUSTRY

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Abstract

There are strategic drivers within the mining industry which are making explosive-free rock breakage approaches an option that is being reconsidered for the excavation of rock masses. A comprehensive review of the performance and related aspects of explosive-free rock breaking (EFRB) technologies is necessary to assess and demonstrate their applicability in the mining industry, particularly in continuous operations and autonomous mining. Additionally, it would facilitate a clear path of research and development. A comprehensive review of rock breakage technologies and expert projects would also provide sufficient understanding from available information and expert opinions of the advantages, limitations, and broad performance specifications of existing and promising EFRB methods for open pit and underground mining applications. The main EFRB technologies include mechanical cutting, microwave, laser, fluid, thermal and electrical applications. Finally, the application of microwave irradiation of rocks has been conducted successfully in the laboratory as a high potential concept. The approach can be expanded to full-scale field implementation as a pre-conditioning tool to facilitate the mechanical breakdown of rock in a continuous fashion as well as possible destressing of rock under high stress. A reduction in mechanical strength of rocks as a result of microwave irradiation could improve the performance of rock excavation equipment such as a tunnel boring machine. This will be increasing the rate of penetration and reducing operation time.

Keywords: Mining, Rock breakage, Fragmentation, Explosive-free, Excavation

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1. Introduction

Since the early 1980s, mining equipment manufacturers have pursued large programs to develop mechanical excavation technologies for hard rock mine development and production. The main driver of these development efforts was to devise and implement continuous mining technologies to achieve higher production rates and lower costs than the conventional drill and blast mining methods [1]. Realizing all the potentials which mechanical excavation can offer, equipment manufacturers, either by themselves or in a joint venture with the mining industry, have committed significant financial resources towards the development of mechanical excavators. Some of these programs have focused on the adaptation of existing technologies, such as Tunnel Boring Machines (TBMs), to mine development. Others have introduced new cutting techniques, such as undercutting, to cause tensile rock failure to enhance attainable production rates. In parallel with machinery development, extensive research has also been carried out in materials technology to develop more efficient and wear-resistant cutting tools for hard rock excavation.

Two common problems were encountered with the field trials of mechanical cutting systems; low production rates and high cutting tool wear. Most of the techniques failed to meet their expected production rates while others have shown a continual increase in attainable production rates due to design changes and/or application of more efficient cutting tools during trials. Two of these technologies, the Oscillating Disc Cutter (ODC) and the Mini-Disc Drum Cutterhead hold the most promise for emerging as a viable alternative to drill and blast. The ODC operation is based on the undercutting principle which is designed to cause tensile rock failure with low thrust forces and machine weight requirements. Undercutting holds great promise if the high cutter wear issues can be addressed and resolved by more efficient tool designs and more wear-resistant cutter materials [2-4]. The Mini-Disc Drum utilizes small disc cutters at thrust levels significantly lower than standard size TBM disc cutters. This means a small and relatively lightweight machine with high maneuverability for easy relocation around the mine. For surface mining, Mechanical Surface Miners have achieved significant advancements in terms of being able to cut harder materials. The machines have become more powerful and with advancements in cutting tool technology, are now capable of excavating harder rocks [5]. The field trials of the mechanical excavation technologies have shown that cutting tool life is the major impediment to their further successful development. More efficient and wear-resistant cutting tools need to be developed to increase production rates and reduce bit replacement costs [1]. An extensive review of different explosive-free techniques was conducted at McGill University in collaboration with Natural Resources Canada – CANMET Mining and Mineral Sciences Laboratories, The South African Council for Scientific and Industrial Research (CSIR) and The Colorado School of Mines (CSM). [1] Two main direct mechanical systems have also been applied: The Radial-Axial Splitter and the Impact Ripper. The former applies tensile forces to cause surface breakouts by applying a radial and axial force within a borehole. It is readily applicable from a conventional boom drill. Some field tests have been carried out in a range of rock hardness with a series of well-performing equipment versions. However, the technology has not yet demonstrated its superiority over conventional drill-and-blast productivity. The Impact Ripper uses a hydraulically driven pointed hammer to generate rock fractures on impact. It is mounted as per a longwall machine and acts in a continuous fashion including carrying broken material on a conveyor. Productivity in good quality rock masses as well as considerable re-mobilizing time are fundamental problems with this technology that can only improve and be applied to a limited range of rock masses if a heavyweight but carriage mounted equipment can be developed [6-9].

EFRB methods include six main technologies. As illustrated in Figure1. Microwave energy application to weaken rocks is a concept that has been proven successful in the laboratory and can be expanded to full-scale field application, as a pre-conditioning tool to facilitate the mechanical breakdown of rock in a continuous fashion. Tests show marked advancement rates for drilling which breaks down the rock in the same fashion as a tunnel boring machine. Significant scaling up developments and tests are required in order to make it operationally practical in the challenging rock cutting environment [1, 10-12].

Lasers, to date, have only been used in limited lab drilling tests in order to explore the best type of laser. This type of application mainly melts and vaporizes rock, making it slow to advance and not ready to be used individually or in combination with other technologies [1, 13].

Fluid application technologies have been applied to break down rock directly with the assistance of high-pressure jets. Limited effectiveness is in hard rock is registered.

However, it can be used as an effective preconditioning agent when intimately paired with rock cutters. The second advantage relates to the continuity in application and the removal of broken material by pipeline. Fluids have also been applied for the larger scale fracturing of rock masses, using boreholes and the expansion of fluids such as foam and cement, and through hydrofracturing. This method will easily applicable to conventional equipment but is relatively slow and could be used for specialized applications such as boulder breaking [1, 14-18].

Long before drill-and-blast became universally applied, thermal fragmentation from heating and cooling was the method of choice to break down rock in situ. Over the last decades, there has been routine application of high heat from torches to drill production holes in open pits. Several field and mine production tests have also been undertaken. While it will probably require significant improvements in the application of the technology to match the advancement of drill-and-blast, this technology, which can be used easily with conventional mining equipment, remains promising in that it can produce significant rock spalling in a continuous fashion. This makes it a possible adjunct to mechanical breakdown of the harder rocks and more competent rock masses [1, 19].

There have been limited practical developments associated with electrical technologies to break down rock. For the most part, theoretical studies and small-scale applications of equipment have been carried out but limited on a larger scale. Pulse Blasting has been deeply investigated. It achieved success in breaking very hard rock from borehole application. Unfortunately, this technology proved to be too expensive from the standpoint of power consumption and equipment component consumption [1].

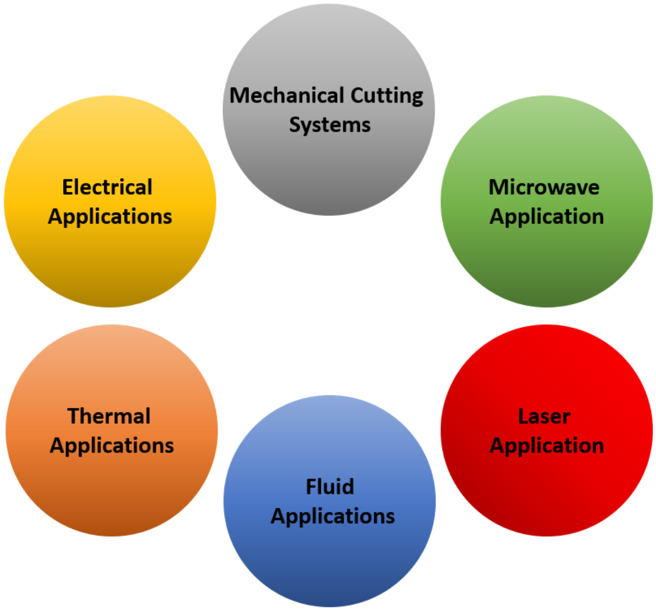

Figure 1. Main explosive-free technologies

2. Explosive-free rock breaking technologies

2.1. Mechanical Cutting Systems

The mechanical excavation technologies include the Mobile Miner, Continuous Miner, Mini Full-Facer, Disc Boom Miner, Oscillating Disc Cutter, Activated Disc Cutting, Narrow Reef Miner, Mini Mole, Mini-Disc Drum Cutterhead, Roadheader, Tunnel Boring Machine for underground mining and the Mechanical Surface Miner for surface mining. A number of these technologies have been discontinued and work is continuing on most of the remaining techniques either through additional field testing or machine design improvements [1].

Mechanical equipment is also capable of operating in harsh environments which could lead to reduced ventilation requirements, an issue which gains more importance as mining is conducted at deeper levels. Selective mining is possible using mechanical excavators and this leads to reduced rock transportation and hoisting requirements.

Mechanical cutting has had limitations in harder rocks and adapting to mine layout requirements. Borehole-based technologies are limited as to their advance rate. Microwave, thermal and water jets benefit from reduced ground control, equipment flexibility and most of all pre-conditioning rock to weaken it to make it more effective for mechanical cutters [1, 20].

The technologies have undergone some level of field testing in either surface quarries or underground mines. These fields can be combined to effectively breakthrough from the recent incremental gains in EFRB application and reach serious performance benefits. Success in surpassing the advance rate of drill-and-blast thus lies in the smart combination of technologies and improvement in cutter technology [1, 21, 22].

There are several advantages associated with this continuous mining. One is that it improves the efficiency and saves time to breakdown rock before comminution and ore liberation, the mine-to-mill concept. Furthermore, it would be attractive to consider pre-concentration underground [1].

2.2. Microwave Application

Microwave energy as a part of the electromagnetic spectrum has different effects on different rock types depending on their characteristics. Different rocks have different behavior by being exposed to the microwave irradiation. Previous researchers by performing some experiments show that microwave energy affects the strength of rocks by generating some micro-cracks due to the difference of volumetric expansion ratio between minerals forming rocks. Basically, microwave energy irradiation heats the medium from inside toward outside. By heating the medium, which is rock, to a certain level, so that it won't get to the melting stage, the difference in volumetric expansion rate between minerals forming rock causes micro-cracks as potential stress within the rock. Therefore, the overall strength of the rock is reduced, so the conventional mechanical machine has to deal with a certain percentage weaker rock [1, 25-28].

A tunnel boring machine is one example of the applications in which microwave energy is combined as an assist. Fundamentally, microwave technology assistance is to irradiate the rock to generate micro-fractures in it or weaken the rock, then the mechanical cutter tool would break the weakened rock afterward.

To the date microwave technology has been used in two different categories of treating materials: 1) for the purpose of separating of specific minerals from others, such as desulfurizing coal and 2) treating materials in order to create micro-cracks into the materials before the crushing section in ore processing plants. Studies have been conducted regarding the generation of cracks inside minerals to require less energy to be broken and crushed in the grinding section of processing plants. The main objective of this study is to show that as microwave energy weakens materials before grinding section to reduce the amount of energy consumed by the processing plant, the electromagnetic energy can assist the primary rock cutting tools with great potential of efficiency. Several studies have been done with regards to breaking rock directly with microwave energy [1, 20, 26, 28].

2.3. Laser Application

The initial idea of using Laser for drilling rocks belongs to the Soviet Union, followed by Americans and then Japanese and a little bit Australians. Now the main studies are held in Argonne National Laboratory in the United States [1].

The efficiency of laser is mainly defined by the laser properties including continuous wave (CW) mode or pulsed wave (PW) mode, max power, wavelength, pulse width, etc. These characteristics would determine the interaction with the rock and transferred energy level. Since the rocks have little reflectivity, the laser beam provides a good penetration into the samples in experiments and an advantage of laser light is the possibility to focus and create an intense power zone. However, existing tests are in the range of centimeters and still far way to obtain an applicable laser rock cutting apparatus for mining and tunneling. Therefore, laser could be applied to cut off the rocks through experiments but there are considerable problems to be solved before the practical use is undertaken [1, 23, 24].

2.4. Fluid Applications

The basic applications of high-velocity fluids, either laden with abrasive solid materials or without them, is to cut and polish routinely various industrial materials in the non-mining industries. However, when the target material is less homogeneous and consists of irregular formations with variable hardness and cohesive strengths (as occurs naturally in hard rock), there is a drastic reduction in the effectiveness of direct fluid in breaking rock, while specific energy requirements increase rapidly. Nevertheless, with the improvement of nozzle materials and creative nozzle configurations, in combination with mechanically assisted drill bits, there has been a gradual increase in the types of rock formation into which holes can be drilled with the assistance and benefits of high-velocity fluids [1, 29, 30].

The major advantage of the fluid is that it removes the broken material from the mechanical cutting edge, thereby reducing the chance of choking at the bit/rock interface, and cools the mechanical drill bit, thereby extending its working life. Although the use of fluid as the sole mover of broken rock is well established in the drilling industry, the use of the hydro-mining concept for large excavations has been limited to very few applications worldwide. Fluid application includes high-pressure, high-velocity (jet) applications, hydro-fracturing, and foam injection, as well as propellants and expanding types of cement. Most of the literature relating to jet technology relates to industrial use in machining applications. However, As early as the 1970s, jet boring was used to excavate coal, which was then hydro-hoisted to surface [1, 31-33].

The analysis of available information revealed that for most underground mining operations, the reason for the routine application of fluids for rock breaking lies in its ability to break up large boulders, which otherwise would obstruct rock flow to ore passes and the like, or to selectively widen existing haulages without the use of explosives. For these individual blasts, pilot holes are required, which are then sealed and charged. When a liquid is used as a pressurization medium, all air has to be removed from the pilot holes, thus any down-drilled holes are advisable, but this requirement also limits the applications of the method. If fracture occurs without complete rock breakage, the immediate pressure drop results in a lost hole [1, 34, 35].

2.5. Thermal Application

Since the end of the Stone Age phase of man's existence and the beginning of the Bronze Age, applying fire to break rocks was a common method (i.e. mining, sculpture and so forth). Indeed, by time passes, explosives took its place because of having large amount of energy which exceeds all levels of strength, mass production in less amount of time. However, the problems caused in the cycle of production by using explosives, environmental issues, the sensitivity of some situations lead the industry to rethink its use. Applying heat technology has been brought to be used again in terms of thermal fragmentation application. There have been different investigations on new methods to thermally fracture and break rocks. Heat creates thermal stress that can fracture rock. The expansion of particles creates the fragments. These micro-cracks are parallel to the free face where heat is applied, and eventually coalesce to form thin plates or chips of rock [1, 23, 24].

Some methods applied historically to break rock use heat either directly or indirectly. Since the manner of heating influences the efficiency of the source, thermal sources can be grouped as follows:

- *Heat sources below the surface (e.g. electron beams):* Experiments done by Robert et al. (1975) determined that by exposing the rock sample to electron beams of an X-Ray, the thermal stress generated can induce fractures [1].
- *Surface heating:* Conducting the heat source to the surface of the material, such as using flame and torches. Depending on the inherent characteristics of a rock, by heating the surface of spallable or non-spallable rocks, rocks can be fractured and chip off.

2.6. Electrical Methods

Some attempts have been made to replace the chemical explosives with electrical blasting material (metallic wires) in order to generate environmentally friendly blasting in Europe and Asia. This technique has been considered under investigation [1].

A considerable number of lab tests have been conducted to investigate electrical pulse blasting in different parts of the world, which provided valuable information about using electricity for lab-scale rock fragmentation purposes [1].

Although there have been some solutions to the problems with plasma blasting technology (PBT), which can be used for other electrical methods, it is very expensive and impractical as compared to other methods. For instance, the lifespan of mechanical and electrical components is short. Using bigger capacitors, which increases the cost, can increase the speed of mining and thus improvement in capacitor technology would assist with the development of PBT. It still seems the industry is a long way from using electrical methods for commercial excavations. Electrical methods can be classified as [1, 36]:

- Plasma Blasting Technology (PBT)
- Electrical Blasting
- Electrical Pulse Blasting
- Electrothermal Rock Breaking

3. Conclusions

The objective of the review of EFRB Technologies is to gain a sufficient understanding and knowing their advantages and limitations. The main technologies include mechanical cutting, microwave, laser, fluid, thermal and electrical applications. The studies and the field trials showed that the mechanical cutting systems have some limitations when they face hard rocks, such as low production rates and high cutting tool wear. There are limiting factors associated with different kinds of EFRB methods. These limitations include operation safety, high energy consumption, high equipment expenses, low speed, environmental issues such as pollution and vibration.

Among the discussed methods, microwave application has proven to be a promising approach for rock preconditioning prior to mechanical excavation. Over the past three decades, researchers are working on the implementation of the microwave irradiation to weaken hard rocks. Extensive research work is being conducted at McGill University to study the effect of microwave irradiation on the mechanical properties of different rocks. Additionally, the optimization of this method in terms of field practicality is currently being studied.

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