THE DEVELOPMENT OF MICROWAVE ASSISTED MACHINERIES TO BREAK HARD ROCKS

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ABSTRACT: Novel rock breakage techniques are becoming more viable. According to a major research report on explosive free rock breakage (EFRB) completed by the authors and others, the use of microwave energy was highlighted as a high potential technique in assisting the breaking of hard rocks. Microwave energy, as a thermal energy which is capable of inducing micro cracks, is a technology that is growing fast in mineral processing and ore comminution applications. Recently, use of microwave has been evaluated as a possible avenue for spatial and terrestrial drilling applications and full face tunneling (TBM) or rock breaking machines. As part of an overall research on use of microwave in rock breaking systems, the influence of microwave energy on the mechanical properties of some common hard rock types is reported. Experimental and simulation results underline the potential impact of the use of microwave energy in underground or surface excavation. This will also contribute economically when mine-to-mill operation is fully considered. Furthermore, the microwave assisted drilling machine which was developed at McGill University and its possible drill bit design is discussed. It also outlines the potential impact of a future microwave assisted tunnel boring machine enhanced with microwave and its performance.

Keywords: *Hard Rock, Rock Breakage, Microwave, Rock Breakage Machine, Tunnel Boring Machine*

1. INTRODUCTION

During the 19th century, drilling systems evolved to mechanized drilling machines. Furthermore, tunneling machines were also built and developed similar to numerous sets of drilling heads to today’s concept of cutter heads. More recently, the technology of drilling of soft to hard rock has evolved quickly. The drilling machines can penetrate to significant depths in hard rock within a short time frame. In recent years, the new novel technologies have been used in mechanical drilling systems in order to improve penetration rates. On the other hand, the development of novel techniques in tunneling is drawing as much interest and attention as drilling systems. The continuous tunneling systems (tunnel boring machines known as TBM) are more commonly employed for soft to moderately hard rocks. Such machines do have problems with very hard rock, such as a lower penetration rate as well as a high rate of wear of cutting discs.

In the past, it was known that a rock can be cut smoother when heated to high temperature. In fact, sculpturing and mining in ancient times were easier when the rock was heated to a higher temperature. Later on, this phenomenon led the researchers to study the thermal application as a novel technique to reduce the strength of rocks. Microwaves are a form of electromagnetic energy that can generate heat inside the material. This research work, employing numerical and experimental work at McGill University, confirms that microwave energy heats rocks according to the properties of its inherent minerals. The heat generates thermal expansion of different minerals, and these differential thermal expansions of minerals induce internal stresses within the rock. These stresses cause micro cracks to develop in the rocks and hence reduce its strength. This leads to development of the concept of microwave assisted mechanical drilling, or rock cutting/ breaking machines

2. ROCK BREAKAGE AND DRILLING

The term rock breakage describes freeing and detaching hard pieces of a rock mass from its parent deposit. Advancement of projects in mining and civil applications is strongly dependent on rock breakage efficiency. Early on, it was understood that heating rocks and quenching with cold water could reduce the rock's strength.

Different techniques can be implemented to break rocks. Traditionally, rock breakage has been done mechanically. Today, other types of techniques are introduced under the term of novel technology. Rock breakage or Penetration for different mining and civil applications can be done mechanically, hydraulically, thermally or even by a combination of them.

Applying mechanical energy to rock masses is the primary and traditional method of drilling rocks. This method utilizes either a continuous percussion system or a constant thrust on the drilling rods, in order to exceed the strength of rock and cause penetration. In percussion systems, each blow of the hammer is transferred through the rods in different spots by the rotating drill bit. However, rotation of the drill bit is not involved in an effective amount of energy applied to the rock. Rotational systems produce shearing forces and can assist in breaking, in order to improve the penetration rate of drilling.

Disc cutters are used on tunnel boring machines to role on the rock surface as well as penetrating into it by applying a large thrust on the cutters.

The penetration of disc cutters depends on various parameters of the machine as well as the mechanical properties of rock mass. The thrust force and rolling force are normally adjusted and defined upon the mechanical properties of rock mass, in order to exceed the strength of rock mass. By applying the forces, the penetration per revolution as well as the life of a cutter can be calculated from the following equations [9]:

$$L = \sum dw^3 \frac{\cot(\theta)}{F_n \sqrt{\sigma_{UCS}\sigma_{PLT}}\,(CAI)^2} \qquad (1)$$

$$P_{\mathrm{Rev}} = 624 \frac{F_n}{\sigma_{Bt}} \qquad (2)$$

$$P_{\mathrm{Rev}} = 3940 \frac{F_n}{\sigma_{UCS}} \qquad (3)$$

Where L is the life index of the cutter wear; d is the cutter diameter; w is the width of the cutter edge; θ is the half of the disc cutter's angle; F_n is the thrust forces apply from the machine; σ_{UCS} is the uniaxial compressive strength of rock; σ_{PTL} is the point load index of rock; σ_{UCS} is the uniaxial compressive strength of rock; CAI is the CERCHAR abrasivity value of the rock's surface; σ_{Bt} is the Brazilian tensile strength value of rock and F_n is the normal force in response to the applied thrust (all in metric system).

3. APPLICATION OF MICROWAVE POWER

The first microwave oven was developed in 1951 on a commercial scale, and since the beginning of 1960's, microwave ovens for home use became available. Not long after, some industries began using microwave power in industrial applications such as rubber extrusion, plastic manufacture and the treatment of foundry core ceramics. Chen et al. (1984) and Walkiewicz et al. (1991) investigated and found the microwave effects on a large number of natural minerals, which their study initiated in the potential use of microwave energy in mineral processing fields. As a result of those studies, it is concluded that the behavior of minerals against microwave radiation differs widely.

Typically, ores, contain minerals with different mechanical and heat properties which can lead to different behaviors of rock. Due to different thermal expansion coefficients existing between mineralogical species, some stresses will be created. Microwave exposure dissipates the energy into the rock in the form of heat. Since different minerals act and behave differently against microwave irradiation, some minerals will heat up and some will not. At this point, microwaves create a strong thermal gradient and thermal stresses within different mineral phases and cause inter-granular cracks. This is validated by [3, 4, 5, 7, 8].

In 1991, thermally-assisted liberation of minerals using microwave energy to provide heat was introduced with an experiment of microwave-assisted grinding done by [6]. The authors used Bond Work Index value for determining the grindability of samples before and after microwaving. They exposed iron ore samples to 3kW and 2.45GHz of microwave radiation. As a result, the work index of iron ore samples was reduced by 10-24%. Furthermore, [3] showed a large reduction in bond work index from 14 to 0.5 after 60sec of microwave exposure in addition to increases in grade and recovery upon the processing of a massive Norwegian Ilmenite ore by influencing the effect of microwave energy [3].

Since materials have different absorption capacities of microwave energy, different amounts of heat are generated within the material when exposed to microwave. The amount of heat produced in a material depends on the power, frequency and exposure time of the microwave radiation. Literature shows that the microwave energy can be used to reduce energy requirements in the comminution of mineral ores (valuable rocks considered ore in mining applications) and increase the liberation of valuable mineral particles for enhanced separation in mineral processing [4, 8].

In an investigation [10] on the influence of microwave radiation on Andesite specimens, Ruskov exposed and melted three individual cored samples. Samples were completely melted after being exposed to a 1.35 kW of power at a frequency of 2.45 GHz for 10 minutes, then 30 minutes with 2.7 kW of power and the same frequency in a multi-mode cavity. X-Ray diffraction analysis revealed that the result of this experiment shows that the basic chemical composition of andesite remained the same with little change without any losses in weight, but the structure of andesite became amorphous after melting.

Previously [2] and [6] determined that different minerals have different reactions to microwave radiation. Some absorb the radiation and some are transparent. With respect to different mechanical properties, minerals heat at different rates in an applied microwave field. The rise in the volumetric expansion will hence create potential stress along the grain boundaries which can lead to weakening the material due to inter-granular and trans-granular cracks through the material. Investigation of the effect of microwaves on massive Norwegian ilmenite ore done by [3] indicate the generation of inter-granular and trans-granular cracks created within the minerals. This investigation also showed reduction in Bond Work Index (BWI) of up to 90%.

Whittle et al (2003) investigated the numerical modeling of the influence of the power density on the strength of the material. Authors simulated a 30 x 15 mm pyrite-hosted calcite sample and examined the effect of microwave radiation on the strength of the sample. Small pyrite particles are distributed all over the calcite host randomly. In that experiment, both type multi-mode and single-mode, microwave applicators were used. Pyrite is a good absorbent and calcite is transparent to the microwave radiation [2]. In this experiment, two different microwave conditions were conducted with the same frequency of 2.45GHz. The results of this simulation show reduction in uni-axial compressive strength (UCS) and point load test (PLT) of the simulated samples.

Recently, some detailed investigation specifically regarding the influence of microwave energy on rock strength has been conducted at McGill University and opened a new horizon as microwave assisting mechanical excavator machineries (such as drilling and full face tunnel boring machines). Wang et al [7] at McGill University simulated a particle of pyrite surrounded by calcite in discrete element method to express the fracture density in the boundary of minerals simulated when exposed to microwave energy. Wang used two different power levels to conduct his experiment. He realized that by increasing the power level also the time of exposure respectively, the density of breakage increases in the particles boundaries area [7]. This study revealed that the heat generated in the material by being exposed to the microwave energy causes the material to expand volumetrically. According to [8], thermal stresses in between the boundary of minerals increases when thermal expansion ratio occurs. The DEM model of [15] shows also that the fracture density increases accordingly in the boundary of particles (Fig.1).

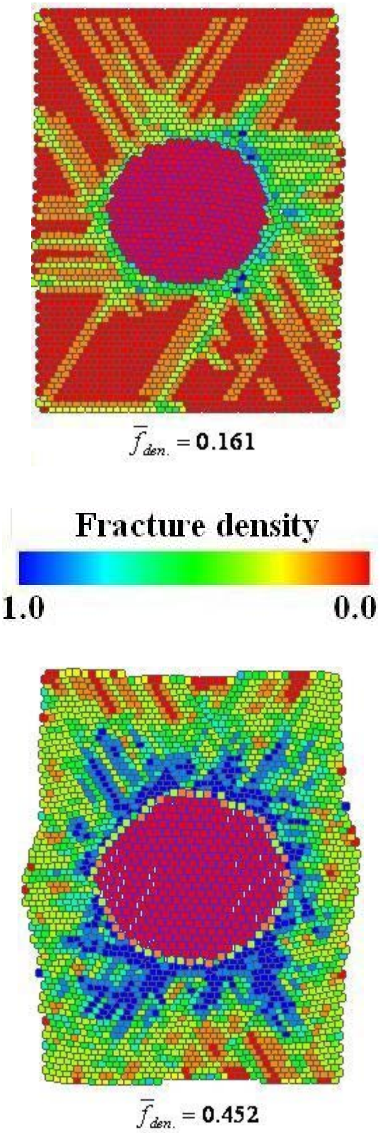


Fig.1 DEM model of fracture density in the boundary of a pyrite particle hosted calcite when exposed to microwave energy at McGill University [7]

It has been concluded from this investigation that rapid and significant failure can happen in single-mode applicators due to high electric field strength. In other words, the higher the power level of the microwave, the more the strength of the sample is reduced [4].

Research, at McGill University, [5] exposed basalt core samples to the microwave irradiation of 750 watts of power for 60, 120, 180 and 320 seconds in a multi mode cavity [5]. In addition to seeing reduction in the strength of the rock by increasing the time of exposure, he also understood that longer exposure (180 and 320 sec) causes the sample to spall and chip off locally under point load test.

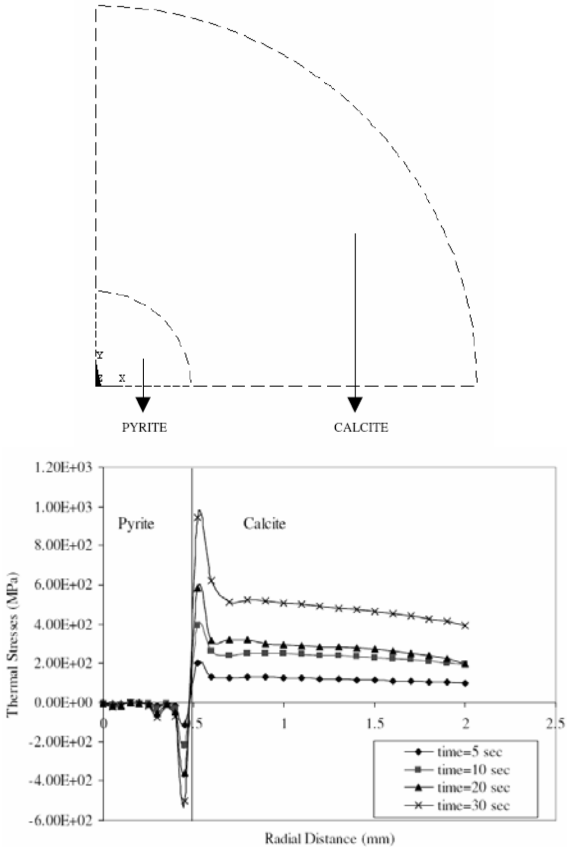


Fig.2 Stress vs. radial distance simulated (lower diagram) in the boundary of a pyrite hosted calcite (upper diagram) at McGill University [5].

In Satish's experiment, single pyrite particle hosted calcite, in the shape of a quarter of a circle, had been exposed to microwave energy (Fig. 2) [5]. Because of the transparency difference of minerals, a big amount of potential stress can be generated in the boundary of the particles, which lead the strength of the sample to be reduced.

In contrast, microwave assisted drilling application has also become of interest to researchers in space mining applications. The cost of space flight is in the order of 20,000 $/kg [1]. Since the equipment needed for space mining on the moon or Mars requires a huge investment, the transportation cost is a big issue. Therefore, reducing the mass of equipment is a big necessity.

Microwave energy assisted mechanical excavators would allow the equipment to maintain its rock destruction power as well as reducing its total mass for transportation purposes. Furthermore, a conceptual design of a microwave assisted drilling machine had been designed at McGill University, in order to practically experiment the performance of drilling a rock while the rock is being exposed to microwave energy.

In order to emit the microwave energy to the surface of the rock while rotating and drilling, the antenna of the microwave needs to be placed in a specific area on the face of the bit, so the microwave irradiation covers all the area of the whole while rotating. A possible drag bit design would be as Fig. 3.

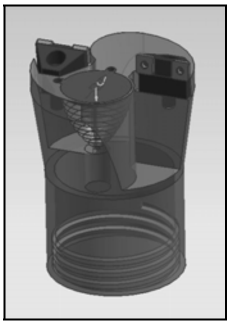


Fig.3 A possible drag bit design consisting a specific area to place the microwave antenna designed at McGill University

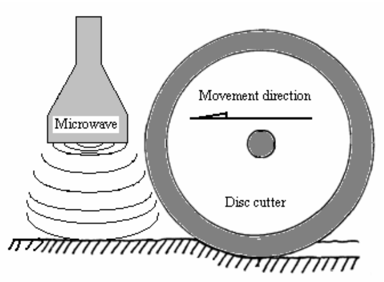


Fig.4 Schematic view of a microwave assisted disc cutter concept of a tunnel boring machine

Moreover, the other application to potentially use microwave assistance, as mentioned earlier, is to implant microwave assistance on a continuous tunnel boring machine (TBM). The concept is to irradiate the surface of the rock mass followed by the disc cutter which is cutting the weakened rock behind. Fig. 4 demonstrates a schematic microwave assisted disc cutter cutting the irradiated rock. Three different hard rocks have been prepared according to ISRM rock mechanics test procedures standards and were subjected to microwave irradiation.

- Basalt samples from California region (2.78 g/cm^3),
- Mafic norite from Sudbury complex basin (2.8 g/cm^3),
- Basalt from China (2.89 g/cm^3), and
- Granite from Vermont region (2.65 g/cm^3).

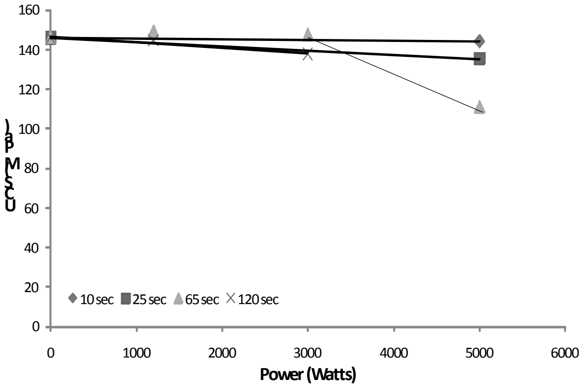


Fig.5 Uniaxial compressive strength when power increases in different exposure times for basalt sample

By observing the influence of microwave energy on the compressive strength of the basalt sample from California, it is also possible to compare the influence of the power input of microwave energy at each time of exposure. Fig. 5 demonstrates that the compressive strength of basalt is relatively reduced by increasing the power input of microwave energy. Basically, the higher the power input of microwave energy the more positive (detrimental) influence on mechanical properties of basalt, in terms of reducing the strength value.

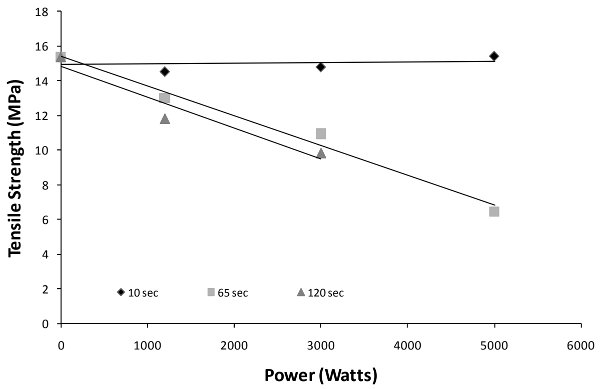
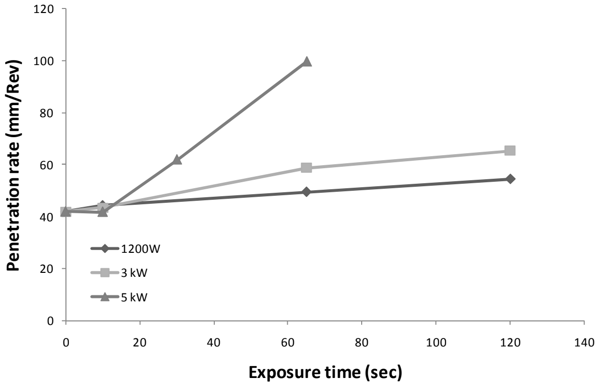


Fig.6 Tensile strength value of norite versus power level

By comparing the power level with the tensile strength values of norite in each exposure time, it can be observed that in the first 10 seconds the tensile value remains unchanged (Fig. 6). After 65 and 120 s of exposure time, the tensile strength value of norite reduced significantly more than 50 % with increasing power level. Furthermore, it also can be concluded that the reduction of tensile value has a linear relation with the power input as the regression squared of the trends in Fig. 6 are reliably high.

According to the equations 1, 2 and 3, as mentioned earlier, the tensile and uniaxial compressive strength of hard rocks are the most important parameters affecting the performance of a tunnel boring machine (TBM). Therefore, by reducing either of those parameters, the total performance would be increasing.



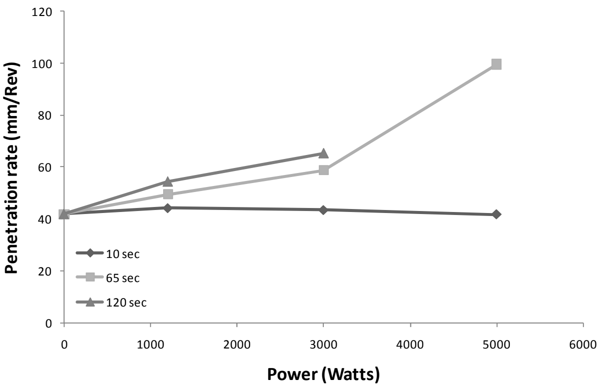


Fig.7 Penetration rate versus exposure time (above) and microwave power level (below) of Norite rock sample.

Selected rocks have been prepared in cylindrical and disc shaped specimens according to ISRM test procedure and standards. They have been individually exposed to the microwave energy of 1.2, 3 and 5 kW, in an equal condition, for 10, 65 and 120 seconds in a multimode cavity. Uniaxial compressive and Brazilian tensile strength tests were conducted on specimens before and after being exposed to microwave energy, in order to compare the results.

The results revealed a significant reduction of tensile strength and a slight reduction in uniaxial compressive strength of the rock samples (the specimen size effect influence the results). Moreover, the longer the specimen is exposed and the higher the microwave power is, the higher the reduction rate of mechanical properties of rocks.

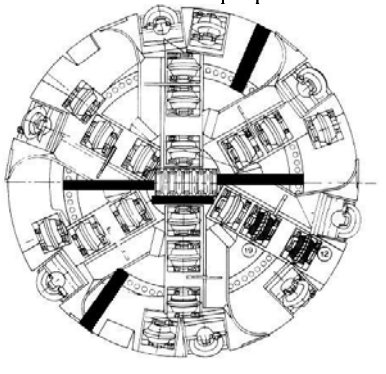


Fig.8 A schematic possible design of a microwave assisted tunnel boring machine’s (TBM) cutter head.

Fig. 7 demonstrates that the exposure time and power level of the energy have a direct effect on the penetration rate of an underground TBM machine considering tensile strength of Norite samples. As illustrated in the graphs, the penetration rate increases when the exposure time or power level increases. Fig. 8 demonstrates a schematic possible design of a tunnel boring machine cutter head.

4. CONCLUSION

Microwave energy, which induces inter-granular and trans-granular cracks into the component of a rock in order to reduce the strength of the material or even increase liberation of minerals, may be a very good candidate for use in rock breakage and comminution techniques. In addition, in order to have a significantly rapid result, the power level of the microwave energy needs to be increased, in other words, increasing the power absorption density of materials. Only the single-mode applicators are able to create such a powerful electric field and a high power level absorption density respectively. However, since microwaves are a good source of heat treatment with significant penetration rates effect, a combination of the two methods, microwave assistance and mechanical, is suggested. Microwave technology could be combined with a mechanical drilling method in order to first reduce the strength of the rock, followed by drilling or cutting (breaking or tunneling) in a conventional way.

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