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# The influence of microwave irradiation on rocks for microwave-assisted underground excavation

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ABSTRACT

Demand is growing for explosive-free rock breakage systems for civil and mining engineering, and space industry applications. This paper highlights the work being undertaken in the Geomechanics Laboratory of McGill University to make a real application of microwave-assisted mechanical rock breakage to full-face tunneling machines and drilling. Comprehensive laboratory tests investigated the effect of microwave radiation on temperature profiles and strength reduction in hard rocks (norite, granite, and basalt) for a range of exposure times and microwave power levels. The heating rate on the surface of the rock specimens linearly decreased with distance between the sample and the microwave antenna, regardless of microwave power level and exposure time. Tensile and uniaxial compressive strengths were reduced with increasing exposure time and power level. Scanning electron micrographs (SEMs) highlighted fracture development in treated basalt. It was concluded that the microwave power level has a strong positive influence on the amount of heat damage induced to the rock surface. Numerical simulations of electric field intensity and wave propagation conducted with COMSOL Multiphysics® software generated temperature profiles that were in close agreement with experimental results.

## 1. Introduction

Since World War II, many devices that use microwaves have been designed and manufactured (Osepchuk, 1984). Microwave frequencies are broadly reserved for telecommunications (Gwarek and Celuch-Marcysiak, 2004). The industrial, scientific and medical (ISM) sector uses frequencies of 915 MHz and 245 GHz (Gwarek and Celuch-Marcysiak, 2004; Brodie, 2011). The concept of using microwave energy to generate heat for rock drilling was briefly examined in the 1960s (Maurer, 1968), but due to technical issues at the time, it was not deemed economical and was not further investigated. Microwave applications have primarily been investigated for the mineral processing industry to reduce energy requirements during comminution of ores and increase the liberation of valuable mineral particles for enhanced separation (Fitzgibbon and Veasey, 1990; Harrison, 1997; Kingman and Rowson, 1998; Kingman et al., 1998, 2004; Whittle et al., 2003; Scott, 2006).

Among the many rock breakage methods available (Hassani, 2010), mechanical rock breakage has been proven to be the most economical and hence the most commonly used one. As current technologies advance and raw materials become more scarce and valuable, the importance of developing novel rock breakage methods increases. The microwave rock breakage technique was introduced in the 1960s (Gray, 1965; Maurer, 1968). Since then, microwaves have been widely and increasingly used in food- (Metaxas and Meredith, 1983; Meredith, 1998), and health-related industries (Saxena, 2009) and for mineral processing (Walkiewicz et al., 1991; Kingman et al., 2004; Scott, 2006).

During hard rock breakage (i.e. the separation of a piece of rock from its parent deposit) in mining and civil applications, the performance of mechanical equipment such as tunnel boring machines (TBMs) is limited by high levels of bit wear and maintenance. Preconditioning to weaken natural rock prior to mechanical breakage is one approach to lower bit wear, maintenance requirements, and costs (Nekoovaght and Hassani, 2014; Nekoovaght et al., 2014a, b, c, 2015; Hassani and Nekoovaght, 2011, 2012; Hassani et al., 2008, 2011, 2012). Preconditioning methods apply heat either directly or indirectly. For example, flame torch-assisted TBMs (Lauriello and Fritsch, 1974; Resource Technology Inc, 1984) have been deemed economical in terms of equipment, but their feasibility is limited by high fuel consumption and because they emit fumes. Preconditioning with microwave energy offers several advantages over the flame torch method: it does not increase fuel consumption (electricity source is available on the machine) or

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produce emissions, and is easy to be controlled (quick power on and off).

### 1.1. Microwave systems

The specifications of a given microwave system depend upon the intended application. Generally, commercial microwave ovens use low power (up to 3 kW) and consist only of a magnetron, a short waveguide, and a closed metallic cavity (oven). Industrial microwave systems use higher power levels (3–200 kW) and comprise the magnetron, isolator, power meter waveguides, tuner, cavity, and power generator. The magnetron generates the microwave energy, which is then transmitted to the cavity by the waveguides, which are long, hollow rods made of a dielectric material to reflect all microwaves. The physical dimensions of the magnetron, isolator, waveguide, and tuner are directly related to the microwave frequency. A microwave with a frequency of 2.45 GHz has a wavelength of 12.2 cm, and travels through a standard WR340 waveguide with dimensions of 9 cm × 4.5 cm.

A single-mode cavity (only one mode of energy is excited within it) has the same dimensions as the waveguide that is used for a given frequency. A multimode cavity is a closed metallic box with dimensions several times the wavelength, resulting in a chaotic energy distribution once microwaves enter the cavity. Although one mineral can also be heated by conduction from adjacent minerals in a multimode cavity, the power density created is 10–15 times greater than that in a single-mode cavity (Kingman et al., 1998, 2004).

### 1.2. Mineral and rock responses to microwave treatment

The amount of heat produced in a given rock by microwave treatment depends on the microwave power level and exposure time, and the mineral and chemical compositions of the rock. Some minerals absorb (e.g. pyrite) and some are transparent to microwaves (e.g. calcite) (Chen et al., 1984; Walkiewicz et al., 1991). Differential volumetric expansion of mineral constituents of rock during heating creates stress along grain boundaries, and causes inter- and trans-granular cracks, which can weaken the rock. For example, the Bond Work Index was up to 90% lower in a massive Norwegian ilmenite ore after microwave treatment (Kingman et al., 1998). Exposing a simulated pyrite-hosted calcite sample to microwave radiation reduced uniaxial compressive strength (UCS) and tensile strength (Whittle et al., 2003; Wang et al., 2005).

The electromagnetic spectrum is comprised of different sections according to its range of frequencies. Within these range of frequencies, microwaves cover the range from 0.3 GHz to 3 GHz. Electromagnetic waves consist of an electric and a magnetic wave traveling perpendicular to each other. Electromagnetic waves transport energy with the speed of light within space. Microwaves as part of the electromagnetic spectrum decay as they penetrate into a dielectric material, at a rate that depends on the electrical and physical characteristics of that material. The penetration depth, also known as the skin depth in metals, is the depth from the surface at which waves attenuate to $1/e$ ($e = 2.718$ as the Euler's number) of their initial power value. The penetration depth depends on the frequency of the electromagnetic waves and the electrical permittivity of the material (Metaxas and Meredith, 1983). For dielectric materials such as rocks (Schön, 2004), which have a loss factor that is much smaller than the dielectric constant, the penetration depth of microwaves is calculated as

$$z = \frac{\lambda_0\sqrt{\varepsilon'}}{2\pi\varepsilon''} \tag{1}$$

where $z$ is the penetration depth (m), $\lambda_0$ is the wavelength of the appropriate frequency (m), $\varepsilon'$ is the dielectric constant of the material, and $\varepsilon''$ is the loss factor of the material.

The volumetric energy absorbed by a dielectric in an electromagnetic field ($P$) is calculated by (Saxena, 2009):

$$P = 2\pi f\varepsilon_0\varepsilon''E^2 \tag{2}$$

where $f$ is the frequency (Hz), $\varepsilon_0$ is the permittivity of free space ($8.85 \times 10^{-12}$ F/m), and $E^2$ is the root mean square of the electric field strength.

The energy absorbed by the material causes the temperature of the material to increase (Metaxas and Meredith, 1983). According to thermo-dynamic law, the amount of energy required to increase the temperature of a material to a given amount is calculated by (Griffiths, 1999):

$$P = \rho C_{\mathrm{p}}\frac{\Delta T}{\Delta t} \tag{3}$$

where $\rho$ is the density of the material (kg/m$^3$); $C_{\mathrm{p}}$ is the specific heat capacity of the material (J/(kg K)); $\Delta T$ is the temperature difference of the material (K), $\Delta T = T_2 - T_1$; and $\Delta t$ is the time difference from its initial value (s), $\Delta t = t_2 - t_1$.

The electric field and power density of the electromagnetic energy decrease exponentially within the material that is exposed to microwaves from an open waveguide (Metaxas and Meredith, 1983):

$$P(z) = P_0\mathrm{e}^{-z/z_0} \tag{4}$$

where $P(z)$ is the power density at depth $z$, $P_0$ is the incident power density, and $z_0$ is the depth at which the power density magnitude decays to $1/e$ of its value at the surface.

The current study is a part of a project at the Geomechanics Laboratory at McGill University that evaluates the influence of microwave radiation on the surface of hard rock. The goal of the project is to develop new rock breakage techniques for underground excavation applications, where microwave energy is radiated from a pyramidal open-ended horn antenna onto the rock surface in underground openings.

### 1.3. Rock breakage

Disc cutters are commonly used on continuous TBMs in hard rock excavations, where they roll on the surface of rock and penetrate into it by applying a large thrust perpendicular to the surface of the rock. The penetration of disc cutters depends on machine parameters, and the mechanical properties of the rock mass. The thrust force and rolling force are adjusted and defined such that they exceed the strength of the rock mass. The life of the cutter and the penetration per revolution ($P_{\mathrm{Rev}}$) can be calculated from Eqs. (5)–(7) (Wijk, 1992):

$$L = \sum dw^3\frac{\cot\theta}{F_{\mathrm{n}}\sqrt{\sigma_{\mathrm{UCS}}\sigma_{\mathrm{PLT}}}(CAI)^2} \tag{5}$$

$$P_{\mathrm{Rev}} = 624\frac{F_{\mathrm{n}}}{\sigma_{\mathrm{Bt}}} \tag{6}$$

$$P_{\mathrm{Rev}} = 3940\frac{F_{\mathrm{n}}}{\sigma_{\mathrm{UCS}}} \tag{7}$$

where $L$ is the life index of the cutter wear (hr), $d$ is the cutter diameter (m), $w$ is the width of the cutter edge (m), $\theta$ is one half of