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Numerical study of the influence of irradiation parameters on the microwave-induced stresses in granite

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ABSTRACT

Mechanical comminution of rocks is an energy intensive process with energy efficiency around 1%. A possible way to enhance the efficiency is the prior application of high-power microwaves. Microwave irradiation of a heterogeneous material introduces inhomogeneous electromagnetic and thermal fields which result in stresses and potentially in damage. In order to assess the industrial applicability, various 3D numerical analyses with either constant microwave power or constant energy were performed on granite samples. To this end dielectric and thermal properties were taken from measurements. For the numerical computations a realistic 3D microstructure was generated by a Voronoi tessellation algorithm. In order to calculate the electromagnetic field inside the rock sample, a finite difference time domain simulation was performed. The resulting temperature as well as stress field is evaluated in finite element analyses. The numerical results were corroborated by microwave irradiation experiments on granite samples.

1. Introduction

Classical mechanical comminution processes are highly energy-intensive consuming up to 2% of the total energy in several mining countries such as USA, Australia and South Africa (Tromans, 2008). Only less than 1% of the applied energy is actually used to generate new surfaces in comminution breakage (DOE, 2007; Fuerstenau and Abouzeid, 2002). In other words, almost the complete energy provided for a comminution process is dissipated in the form of heat and noise. High energy and maintenance costs as well as strict sustainability regulations call for more efficient mining processes. A highly promising technique, which has the potential to decrease the energy consumption of mineral comminution processes, is microwave treatment of rocks prior to physical comminution (Vorster et al., 2001; Kingman, 2006). The purpose of microwave irradiation is to pre-damage the rock (cracks, spallation) in order to weaken its mechanical properties.

Microwave treatment of rocks is driven by the absorption of microwaves by the rock combined with the conversion of the electromagnetic energy into heat. Unlike classical convective heating the heat flux is directly created inside the material. Furthermore, different minerals show varying microwave absorbing behavior. These effects introduce temperature gradients into the rock that generate stresses which can exceed the strength of the rock.

The ability to transfer and absorb microwaves in a dielectric material is described by the complex dielectric constant ε (permittivity): $\varepsilon = \varepsilon_r + i\varepsilon_i = \varepsilon_0(\kappa_r + i\kappa_i)$. ε_0 defines the permittivity of vacuum, κ_r the real part of the relative permittivity and κ_i the imaginary part. The absorption of microwave energy inside the material is mainly governed by κ_i. According to Santamarina (1989) typical values for hard rocks range from 10^{-3} to 50 for κ_i and 2–10 for κ_r depending on various parameters (rock type, mineral distribution, microwave frequency, temperature, water content, ...). Since rocks contain several minerals arranged in various distributions, different κ_i values appear in the material on the microstructure level (Monti et al., 2016). Typically good microwave absorbing minerals are plagioclase ($\kappa_i = 0.004 - 0.32$ (Kržmanc et al., 2003; Zheng et al., 2005)), pyroxene ($\kappa_i = 1.62$ (Zheng et al., 2005)), hematite ($\kappa_i = 8 - 15$ (Monti et al., 2016)) and ilmenite ($\kappa_i = 32.58$ (Zheng et al., 2005)) whereas quartz ($\kappa_i = 0.0004 - 0.0026$ (Ishii, 1995; Zheng et al., 2005)), orthoclase ($\kappa_i = 0.00019$ (Church et al., 1988)) and muscovite ($\kappa_i = 0.0005 - 0.0034$ (Church et al., 1988)) are poorly absorbing. Consequently, an inhomogeneous thermal field on the grain level is expected. Recently, several numerical studies of rocks with heterogeneous microstructures showed that the resulting stresses around the

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phase boundaries of strong-absorbing particles are high enough to initiate cracks which can propagate further into the material (Ali and Bradshaw, 2010, 2011; Jones et al., 2005; Meisels et al., 2015; Toifl et al., 2014, 2015, 2016; Wang et al., 2008; Wang and Djordjevic, 2014). These thermally induced cracks may lead to a significant reduction in grinding resistance during comminution processes (Fitzgibbon and Veasey, 1990).

Although many promising experiments and numerical studies on the microwave-induced damage of hard rocks have already been performed, neither large-scale application nor commercial equipment exists. It has been argued that this discrepancy is caused by problems with materials handling, arcing in systems under high electric fields, the availability of hardware to deliver relevant tonnage treatments in harsh environments, huge technical and economic risks in the development of new technology in a conservative sector which experiences major peaks and troughs in its fortunes. In our opinion, however, this is also due to the lack of understanding the influence of the microwave irradiation parameters on the microwave-induced damage in the rock material. Therefore comprehensive three dimensional numerical simulations with either constant power or constant energy are conducted on granite samples in the paper at hand. Granite as a typical heterogeneous hard rock was chosen because we could get a reproducible set of samples, obtain various material data as well as a range of microwave experimental results suitable for validation of the numerical procedure. The goal of the current research is to understand the relations between microwave irradiation parameters and resulting temperature as well as stress fields.

The reported experiments also show different crack patterns and specific damage behaviors strongly depending on the rock type. In granite, for instance, dense crack networks form underneath the irradiation spot consisting of a series of microcracks that may coalesce to a single dominant crack upon further microwave-treatment that penetrates deep into the material. A closer look at the crack path reveals that these cracks grow along grain boundaries (Hartlieb et al., 2016). A quite different behavior has been recorded for rather homogeneous rock types, such as basalt, limestone and also andesite where, depending on the microwave power level, melting or spallation are the prevalent damage modes (e.g. Znamenackova et al., 2003; Peinsitt et al., 2010; Lovás et al., 2011; Hassani et al., 2012). However, a quantitative analysis capable of predicting crack initiation and subsequent crack evolution is still lacking in literature.

In order to identify microwave-induced stresses in granite on the microstructure level, a 3D three-component inhomogeneous microstructure model is generated. Afterwards, the electromagnetic field is solved by a FDTD algorithm (finite difference time domain, see Taflove (2005) and Yee (1966)) followed by a finite element (FE) analysis which calculates the thermal as well as stress field. Temperature dependent thermo-mechanical and physical material properties are taken from measurements for the specific granite samples and used as an input for the numerical simulations. Finally the simulations are corroborated by microwave irradiation experiments performed on granite blocks.

2. Methodology

Calculating the microwave-induced stress field inside a 3D microstructure requires a comprehensive simulation methodology connecting various numerical modules. In the work at hand a simulation chain without taking into account any feedback of temperature changes on the electromagnetic properties as well as a weak coupling between the displacements and the thermal field is presented (Fig. 1). For details on the simulation strategy the reader is referred to Toifl et al. (2016).

The simulation process starts with the collection and preprocessing of input data (Fig. 1). In the first numerical working package a cube is divided into polyhedra by a Voronoi tessellation algorithm (open source program *Neper*: Quey et al., 2011) which resolves individual grains of the microstructure. Afterwards the various grains are assigned to different phases. In the current study a three-component microstructure with phase distribution according to the tested granite block (Section 3) is used. The created microstructure represents the basic input for all further simulation modules. Subsequently, the electromagnetic field inside the model rock is calculated by solving Maxwell's equations numerically by performing a 3D FDTD (**F**inite **D**ifference **T**ime **D**omain) analysis (Taflove, 2005; Yee, 1966). As a result the time averaged squared electric field E^2 is determined, which is subsequently used to derive the absorbed power density (Eq. (1); Jackson, 2011) distribution as the output of this analysis.

$$P_{abs} = \omega \varepsilon_0 \kappa_i E^2 \tag{1}$$

In Eq. (1) ω defines the angular frequency of the wave and ε_0 the permittivity of vacuum. In the subsequent thermal FE (**F**inite **E**lement) simulation, the absorbed power density multiplied by a constant factor C is directly treated as heat source entering the heat conduction equation, which can then be solved numerically (Fig. 1). In this paper the effects of various microwave irradiation times under constant power (Table 1) as well as constant energy (Table 2) are assessed.

After calculating the transient temperature field during heating the thermal energy inside the model is evaluated and compared with the provided microwave energy minus 30% losses which is what we estimate with the currently used lab-setup. If the difference is greater than 5% the constant factor C is adapted and the thermal heat transfer calculation is repeated (Fig. 1). Afterwards the natural cooling of the hard rock model is calculated for duration of one hour. Finally, the transient inhomogeneous temperature field is used as an input for the FE stress simulation.

2.1. FDTD model

The FDTD algorithm explicitly solves Maxwell's equations which describe the evolution of the electromagnetic field. In the current research the FDTD open source software *Meep* (Oskooi et al., 2010) is used. Fig. 2 visualize the microstructure and the FDTD model.

Quartz (blue[1] phase in Fig. 2), plagioclase (red phase in Fig. 2) and muscovite (beige phase in Fig. 2) represent the phases of the artificial microstructure of the granite model. For obvious reasons it is impossible to finely mesh the entire rock so one standard technique is to embed a finely meshed cube in a surrounding homogenized bulk material with averaged material properties (Fig. 2). The scaling of the cube depends on the desired average grain diameter, which is set to 3.2 mm in this work. This leads to a cube with an edge length of 8 cm containing the highly resolved microstructure. Furthermore, a quarter symmetry of the whole numerical model was assumed in order to reduce the problem size and thus avoid excessive simulation times (Fig. 2). The dimensions of the granite material were chosen to be $40 \times 40 \times 80\,\text{cm}^3$ which ensured that with the given dielectric material parameters no reflections of the microwaves occurred at the boundaries of the material. In addition **p**erfectly **m**atched **l**ayers (PML) were applied at the boundaries of the model in order to truncate the simulation space without causing artificial reflections (Oskooi and Johnson, 2011). Air was added at the front face in order to model the wave propagation between microwave

[1] For interpretation of color in Figs. 2, 3, 5, 13 and 18, the reader is referred to the web version of this article.