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Damage of basalt induced by microwave irradiation

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ABSTRACT

In this work microwave irradiation on cylindrical samples of basaltic rock is investigated by laboratory experiments and compared with results from numerical models. Due to the temperature gradient in the samples induced by the microwave irradiation a significant damage indicated by a reduction of the sound velocity and finally the formation of cracks occurs. Applying a microwave power of 3.2 kW leads to a surface temperature of 250 °C and to 400 °C in the centre of a cylindrical sample after 60 s of irradiation. Temperature rise goes along with the formation of both axial and radial cracks. Cracks are not bound to the mineralogical composition but their development is governed by macroscopic temperature gradients and the geometry of the sample. A thermal and a thermomechanical finite element model are formulated and used to calculate temperature distributions and induced thermal stresses. The results indicate that tensile stresses exceed tensile strength leading to cracks as observed experimentally.

1. Introduction

Weakening rocks by means of microwave irradiation has been a major topic in research for the past 50 years. The focus of all the projects lies in the development of more economic technologies for breaking, cutting and comminution of various types of rocks. A detailed review of all the work done before the 1980s is provided by Santamarina (1989). Recent activities mainly focus on comminution of various rock types. They have been performed by Walkiewicz et al. (1988), Satish et al. (2006), Jones et al. (2005) and many more. Pickles (2009) gives a detailed overview possible applications in extractive metallurgy.

The absorption of microwave energy of a sample depends on high-frequency dielectric properties of the constituents of a rock. These can be described by $\epsilon = \epsilon' + i\epsilon'' = \epsilon_0(\kappa' + i\kappa'')$. Where κ' is the real part, κ'' the imaginary part of the relative dielectric constant and ϵ_0 is the permittivity of free space. According to Santamarina (1989) typical values for rocks range from 10^{-3}–50 (κ'') and 2–10 (κ'). Values for κ'' of basalt range from 0.08 to 0.8, whereas values for κ' vary between 5.4 and 9.4.

Several papers are devoted to explaining rock breakage by the different microwave absorption rates and thus different heating rates of the mineralogical constituents of a sample. Whittles et al. (2003), Jones et al. (2005) postulate that inducing fractures between an ore and the host rock can be achieved by using the differential absorption of microwave energy between the different mineral phases. Together with Jones et al. (2007), Ali and Bradshaw (2009) it is demonstrated that damage after microwave-treatment is caused by tensile stresses occurring during the thermal expansion of the absorbing phases as well as shear stresses along the grain boundaries. It is also shown that particle size as well as delivery method and power density play a major role in the damage of an ore (Ali and Bradshaw, 2010).

What the model calculations (Ali and Bradshaw, 2009, 2010; Jones et al., 2005) have in common is their focus on mineral comminution and that simulations are performed with idealistic two-phase rocks with one strongly absorbing mineral in a non-absorbing matrix. Experimental studies of Satish et al. (2006), Peinsitt et al. (2010) show that also more homogeneous rocks such as basalt and granite show a significant increase in surface temperature as well as decrease in strength when irradiated in a multimode cavity. According to Peinsitt et al. (2010) basalt samples reach 330 °C after 60 s of irradiation with a power of 3.2 kW, whereas granite takes 300 s for reaching a temperature of 220 °C. The increase in temperature goes along with a significant decrease in uniaxial compressive strength and p-wave velocities reflecting a decrease in rock strength. The two authors demonstrate that relatively finely grained and homogeneous rocks can be heated and damaged with the help of microwaves. Therefore the presence of extremely good absorbing particles within this matrix working as a focus for microwave absorption and causing strong inhomogeneous heating is not a necessity.

Nevertheless there is a strong need to getting a better understanding of the processes leading to microwave induced damage of rather homogeneous rocks. It is also necessary to back up

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simulations with experimental results. This work focuses strongly on fine grained basaltic rocks and their response to irradiation in a microwave cavity, the way damage occurs and the numerical simulation of laboratory results.

2. Experimental arrangement

Following the procedure described by Peinsitt et al. (2010) the microwave irradiation experiments were performed in a 3.2 kW multi-mode cavity of a commercial microwave oven at a frequency of 2.45 GHz. Cylindrical basalt samples, 50 mm of length and 50 mm of diameter are positioned in the center of the cavity atop of glassware being a very weak microwave absorber. For each load step a minimum number of five samples have been investigated for statistical reasons.

The effect of microwave irradiation is evaluated (a) by measuring the temperature of irradiated samples by the help of an infrared thermometer and camera, (b) by measuring sound velocities (p-wave) along the z-axis of the samples, (c) by investigating resin-saturated thin-sections and (d) by the help of a penetration spray normally used in metallography displaying cracks developing at the surface of a sample. Before preparing a thin section the samples are saturated with a blue resin. This resin only penetrates open cracks, hardens and helps identifying cracks and structural damages within the sample.

3. Numerical analysis

3.1. Governing equations

The governing equations are obtained from the fundamental principles of continuum thermomechanics. Starting from the energy-balance equation for a non-moving body the heat conduction equation

$$\rho c_p \frac{\partial T(\underline{r},t)}{\partial t} = \nabla \cdot (k \nabla T(\underline{r},t)) + s(\underline{r},t) \tag{1}$$

is obtained. The symbols in Eq. (1) are the temperature T the density ρ, the specific heat c_p, the thermal conductivity k, the position vector $\underline{r}$ and the Nabla operator ∇. The symbol s denotes the heat generation rate in the medium, generally specified as heat generation per unit of time and per unit of volume. When *SI*-units are used, s is given in W/m^3. In this work the thermal properties of the medium are temperature dependent, therefore Eq. (1) becomes a nonlinear parabolic partial differential equation. For the linear heat conduction equation several analytical solutions exist, while in the nonlinear case only for few special problems analytical solutions can be obtained (Carslaw and Jaeger, 1986; Ozisik, 1993). For this reason a numerical solution of Eq. (1) is performed. To solve the thermoelastic problem additional equations are required. These are the equilibrium equation

$$\nabla \cdot \underline{\underline{\sigma}} = \underline{0}, \tag{2}$$

with the Cauchy stress $\underline{\underline{\sigma}}$, the strain–displacement relations

$$\underline{\underline{\varepsilon}} = \frac{1}{2}(\nabla \underline{u} + \underline{u}\nabla) \tag{3}$$

with the infinitesimal strain tensor $\underline{\underline{\varepsilon}}$ and the displacement vector $\underline{u}$, and the thermoelastic constitutive relation

$$\underline{\underline{\sigma}} = \lambda \mathrm{tr}(\underline{\underline{\varepsilon}})\underline{\underline{1}} + 2\mu\underline{\underline{\varepsilon}} - (3\lambda + 2\mu)\alpha\underline{\underline{1}}(T - T_0) \tag{4}$$

with the Lamé constants λ and μ, the coefficient of thermal expansion α and the temperature T_0 which characterizes a stress-free reference state. The Lamé constants, the Young's modulus E, the shear modulus G and Poisson's ratio ν are connected by the well known relations:

$$E = \mu\frac{3\lambda + 2\mu}{\lambda + \mu}, \quad G = \mu, \quad \text{and} \quad \nu = \frac{\lambda}{2(\lambda + \mu)}. \tag{5}$$

All governing equations are formulated in a coordinate free manner. With the help of tensor calculus the equations can be written in any convenient coordinate system (Eringen, 1980). In this work cylindrical coordinates

$$x = r\cos\varphi, \quad y = r\sin\varphi, \quad z = z \tag{6}$$

with

$$0 \leqslant r \leqslant R, \qquad 0 \leqslant \varphi \leqslant 2\pi \quad \text{and} \quad 0 \leqslant z \leqslant H, \tag{7}$$

are used.

The temperature dependence of the thermal conductivity k and the specific heat c_p are taken into account. In Section 3.3 the values of $k(T)$ and $c_p(T)$ at different temperatures are given. The density of the material is constant. As mentioned before the symbol s in Eq. (1) denotes an internal heat generation rate (in W/m^3) or a body flux.

There exist several approaches to model microwave absorption in dielectric media. For example Dincov et al. (2004) utilize Maxwell's equations in dielectric media, or Ni et al. (1999) use Lambert–Beer's law to model the absorption which allows to calculate the heating. In this work a simplified approach is performed. It is assumed that s is constant throughout the whole volume. This is justified by (1) the sample being irradiated in the microwave oven from all directions and (2) the penetration depth D_p being larger than the sample dimensions. For average values of κ' and κ'' (7.4 and 0.48, resp., Santamarina, 1989) D_p is 11 cm, which has to be compared with the radius and half the height of the cylindrical sample (2.5 cm). Based on thermograhic measurements the heat generation rate s is calibrated with aid of the FE-method.

3.2. Model

There exist two Finite-element (FE)-models in this work, the first one is used to calibrate the volumetric heat source s, the second one is used to study the thermomechanical loading of the basalt sample.

An analytical solution of the problem is not available, therefore it is solved numerically by the finite element method (FEM). As solver the general purpose FEM package ABAQUS v6.10 ABAQUS (2010) is used. The finite element discretization of the heat conduction equation is given by

$$[C]\{\dot{T}\} + [K]\{T\} = \{Q\} \tag{8}$$

with the heat capacity matrix $[C]$, the conductivity matrix $[K]$, the temperature vector $\{T\}$ and the load vector $\{Q\}$ which takes the source-term into account. Formulating Eq. (8) at the nth time level delivers:

$$[C]\{\dot{T}_n\} + [K]\{T_n\} = \{Q_n\} \tag{9}$$

Due to stability reasons, the time derivative $\{\dot{T}_n\}$ is approximated by the backward difference

$$\dot{T}_{t+\Delta t} = \frac{T_{t+\Delta t} - T_t}{\Delta t} \tag{10}$$

in the time-integration scheme, for details see ABAQUS (2010). In this paper Eq. (9) is nonlinear, i.e., $[K]$ and $[C]$ are temperature-dependent, therefore a Newton–Raphson algorithm is used to solve the nonlinear equations. Details can be found in the manual of the FE-code ABAQUS (2010) or in Bathe (1995).