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# Numerical model of laser spallation drilling of inhomogeneous rock ⋆

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**Abstract:** Spallation of rock during laser drilling is dependent mainly on temperature on the surface, material properties and presence of discontinuities within the rock. A numerical model of laser spallation of heterogeneous granitic rock using the Finite Element(FE) method is presented. The developed model accounts for the presence of microcracks within the rock. Convective boundary conditions are also considered and the effect of propagation of these cracks on spallation is investigated. Temperature and stress profiles generated are discussed. The results indicate stress development on the surface of the rock and its effect on eventual rock fracture.



*Keywords:* modelling, laser, spallation, finite element, stress.

## 1. INTRODUCTION

The study of rock fracture due to thermal means is necessitated by the numerous applications of thermal methods in underground excavation such as blasting and tapping of geothermal resources. In addition, recent developments seek to introduce more thermal means of rock drilling, with laser assisted drilling being the most common. Rock is heterogeneous due to its constitution of different grain types, grain sizes, pore sizes and microcracks. Application of thermal loads on loads initially causes cracking, with further heating causing melting.

The use of lasers has been lauded due to the reduced wear because of their non-contact nature, as well as their versatility in terms of means of material removal (Soleymani et al., 2013). Lasers can be used to either cause melting of the rock or spallation, which means thermal stresses are induced in the rock in order to cause fracture. The focus of research on laser spallation has been primarily been on the mechanism of spallation, the parameters of spallation and the behavior of the different rock types during spallation (Olaleye, 2010). Spallation has been attributed to several mechanisms. The presence of different minerals with different rates of expansion causes increased strain at the boundaries of the minerals, hence promoting cracking. In addition, variation of the location of the different minerals within the rock, caused a distinct variation in the behavior of the rock mass (Brkic et al., 2015; Walsh et al., 2012). This has necessitated the inclusion of heterogeneity in any study attempts into thermal spallation. In terms of temperature distribution within the rock, sharp temperature gradient between the heated area and the adjacent regions created by the low thermal conductivity of most rocks is another mechanism causing spallation. This mechanism also seems to be applicable for relatively homogeneous rocks as studied by Hartlieb et al. (2012).

Several studies have been conducted in laser spallation. Experimental studies conducted by Ghassemi (2012) and Kobayashi et al. (2009) have been useful in determining the onset of cracking in rock exposed to laser radiation. Among the observations made were the variation of crack density with increase in temperature as well as the variations within the grains and grain boundaries. These works have enabled the determination of several threshold temperatures which have formed a suitable baseline for modeling attempts. The need for numerical modelling is underpinned by the fact that experimental studies are not able to fully describe the thermal stress evolution for microcrack development in the rock due to the expansion of the rock. In addition, improvement in computational capacity as well as numerical methodology enables the analysis of complex phenomena.

Numerical methods have sufficient popularity in the study of thermal effects on rock on both the macro- and microscale levels. The finite element method has been used in the investigation of rock cracking due to thermal exposure. Agha et al. (2004) developed a finite element model to predict the rate and depth of penetration during laser machining without consideration of melting. This model ignored inhomogeneities within the rock. A more inclusive model developed by Walsh et al. (2012) focused on the behavior of granitic rock on a grain scale level during hy-

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drothermal spallation. The model determined that stress concentration was affected by properties of the rock surface such as thermal conductivity and grain distribution within the material. The research, however, used a fluid jet as the source of thermal energy, which differs distinctly from the coherent and directional nature of laser energy. Variation of sources of energy, varies the behavior of the rock, with some sources capable of irradiating wider areas while other sources such as laser only illuminate a smaller spot. Research into the effects of the laser on rock has primarily focused on analyzing laser-rock interaction with a view to understanding the specific energy and rate of penetration into the rock(Brkic et al., 2015; Adeniji, 2014). There have been few numerical studies into the influence of laser on rock damage.

This study seeks to develop a numerical model for thermal stress development in granite rock when exposed to laser power. Heterogeneity on the rock surface is proposed through statistical distribution of grains with different mechanical properties throughout the granite rock. The temperature and stress distributions within the rock is discussed and the effect on spallation is determined. The accuracy of the model is validated by comparison to theoretical solutions.

## 2. GOVERNING EQUATIONS

Governing equations of the model will be classified into two: heat transfer within the rock and rock deformation due to the stress generated. Laser beam of intensity, I, is directed on the rock and is assumed to have a Gaussian distribution. Heat conduction through the rock is described by (1).

$$k\nabla^2 T = \rho c \frac{\partial T}{\partial t} \quad (1)$$

Material properties are represented by thermal conductivity, k, density, $\rho$ and specific heat, c. Heat loss due to radiation is assumed to be negligible and hence ignored. The relationship between the stress and strain components in the rock due to the temperature effects are defined by

$$\sigma_{ij} = \lambda \epsilon kk \delta_{ij} + 2G\epsilon_{ij} - \beta \Delta T \delta_{ij} \quad (2)$$

The change in temperature, $\Delta T$ is the difference between the current temperature and the initial temperature. The thermal stress coefficient, $\beta$ is denoted by

$$\beta = (3\lambda + 2G)\alpha \quad (3)$$

where $\alpha$ is the thermal expansion coefficient. $\lambda$ and G are the Lame constant and shear modulus respectively. The strain tensor, $\epsilon_{ij}$ can also be defined in terms of the displacement vector, $u_i$

$$\epsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \quad (4)$$

## 3. NUMERICAL MODEL

### *3.1 Verification of the Model*

In order to determine the suitability of the numerical model developed in ANSYS, comparison is made between both the temperature and thermal stress values and the theoretical values. A simple annular model with internal radius a of 5 mm and external radius, b of 30mm is analyzed numerically with constant temperature applied to one boundary. The temperature profile, T(r) for the annular sample along the radial distance, r can be theoretically calculated from (5).

$$T(r) = \frac{T_a \,\mathrm{In}(\frac{b}{r}) + T_b \,\mathrm{In}(\frac{r}{a})}{\mathrm{In}(\frac{b}{a})} \quad (5)$$

Figure 1 shows the comparison between the theoretical solution obtained from Equation 5 and the solution obtained from ANSYS. There is good agreement between these results, validating the accuracy of the ANSYS Model.

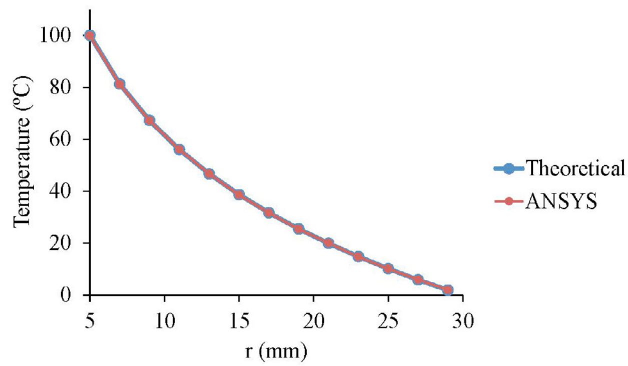


Fig. 1. Comparison between temperature profiles obtained from theoretical and numerical calculations.

According to Timoshenko and Gere (1972), radial stress at each point on the body can be calculated from Equation 6. The verification of the thermal stress results are realized in Figure 2.

$$\sigma_r = -\frac{E\alpha(T_a - T_b)}{2(1-\nu)} \left( \frac{In(\frac{b}{r})}{In(\frac{b}{a})} - \frac{\frac{b^2}{r^2} - 1}{\frac{b^2}{a^2} - 1} \right) \quad (6)$$

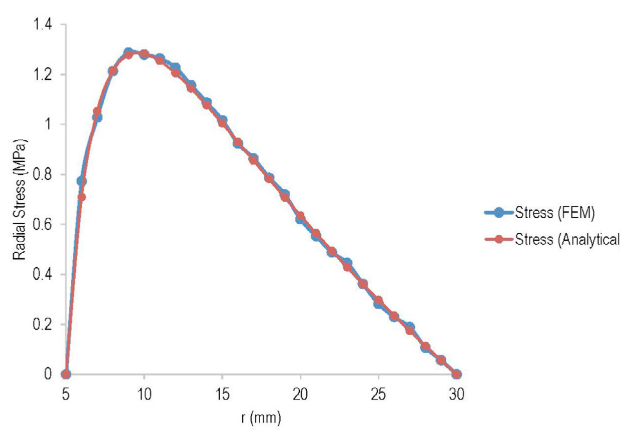


Fig. 2. Verification of thermal stress model

### *3.2 Creation of the physical model*

A three dimensional geometry is created in ANSYS with radius of 15mm and thickness of 10mm. In order to capture heterogeneity of the rock, two minerals are considered, that is, quartz and feldspar. The properties of the minerals vary according to Table 1 as recorded by Yu et al. (2015). The laser heat flux is loaded on one boundary of the workpiece and the thermal load used as input to the stress model.