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The Geo-materials Fracture by Thermal Process

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ABSTRACT

Thermal spallation of the rock is promising alternative technique for rock drilling in civil engineering works and petrol industry as tunneling and wells drilling... Over the last century, many works were conducted to test and examine the functionality and the feasibility of thermal spallation to remove the rocky materials. Recently the radiation is the most examined fashion to deliver heat at the rock surface where we need high heat flux to spall the rock. However, the thermal spallation is firstly described by Preston et al. (1943). The Laboratory studies demonstrate that the required energy to produce fracture is huge due to high compression strength of the rocky materials. This energy varies between 0.5 and 14 MW/m² according to rock type. In addition, the energy loss in the fibers (to deliver the laser energy) is almost 60% for a kilometer away, which poses a problem of energy delivery to the rock surface in deep according to this high energy level.

The present work offers an alternative method for generating thermal fracture of the rock. It is based on the introduction of the thermal contraction deformation. Accordingly tensile stresses potentially superior to tensile strength of the rock will be created. The tensile strength is much lower than that of compression as well known. So this is a hypothesis that supposedly reduces the required energy to fracture the rock. The proposed mechanism is a coupling of a local rapid heating followed by rapid local cooling of the treated surface. The rapid variation of the heat flow on the treated surface will suddenly reverse compressive stresses induced during the heating phase to tensile stresses during the cooling phase. Once induced tensile stresses exceed the tensile strength of the rock fracture should take place. A model of 2D axisymmetric finite element is used to demonstrate the procedure. The stone used is granite. The proposed mechanism is evaluated in several ways: (1) the thermal efficiency, (2) the possibility of fracturing the rock, (3) reducing the energy required to fracture the rock (4) and depth penetration.

1. INTRODUCTION

Increasing demand of oil, gas and dry wells makes the rock removing techniques developers in frantically racing to improve and maybe invent technologies to efficiently drilling hard rocks. In United States of America, 37014 km of wells were drilled in 1999 with mean depth of 1830 m (Olaleye B,2010). Relating to this high average of drilling works it is crucial to improve the reliability of actual conventional technologies especially in minimizing capital time and money costs. These costs are majorly connected to the drilling process (loss of stocked equipment into the hole, damage of the headers, installation time, and relative damage in the mass of rock which increases casting cost…). The thermal spallation was always the suggested alternative technique to remove and disintegrate rocky material. This thermal spallation firstly described by (Preston et al,1934) was produced by using different heat delivery fashions. The most attractive fashion is the Laser radiation that is considered as very efficient spalling technique (Ahmadi et al,2011) (Ahmadi et al,2012) (Rauenzahn et al,1989) (Xu et al,2004) (Xu et al,2005). Even the experiments results were very impressive and encouraging, the laser radiation technique still far to convince the technical people to adopt it definitely. By experiments, the laser radiation is able to perforate a hole of 10 cm of depth using 14.5 MW/m² of CO_2 Laser over 80 seconds (Xu et al,2004). From other side the operating cost of Nd:YAG laser for example is grossly high varying between \$95 to \$200 per watt which consequently forms another deterrents to adopt and develop the laser perforation that depends on the Preston principle. As well, the energy loss through laser fibers is 60% over one kilometer of depth which poses a delivery problem for huge amount of power. However, thermal spallation depends on locally concentrated high heat flux during short time. The local temperature will increase instantaneously and will be restricted to the treated zone due to relatively feeble thermal conductivity of rocks. This results in lateral compressive thermal stress in the subsurface area beneath the treated zone according to thermal dilatation. Merely, these stresses have to overtake the compressive strength then after spalling occurs. Moreover, the local overheating may cause increasing of rock ductility where transition from purely brittle towards a more quasi brittle behavior takes place and eventually the spallation becomes more difficult (Damhof et al,2008). However, a reduction in required energy can be accomplished by benefiting from the truth that tensile strength of rocks is much less than the compressive one, as well known. So accordingly, the question is how to induce such tensile state in rock body.

In this work, new innovative thermal disintegration mechanism of rock will be described. The proposed mechanism is a coupling of a local rapid heating immediately followed by rapid local cooling of relative spot of rock surface. Consequently, local thermal dilatation will be produced within the treated zone and subsequently local thermal shrinkage will be applied due to cooling process. Therefore, instantaneous toppling from compression state to tension one will occurs in the treated zone. Expectedly due to the shrinkage, the treated spot will be completely charged by tensile stresses. Once the induced tensile stresses overtake the tensile strength of the rock the treated zone will be ripped from the rock body. A modeling effort will be presented in the paper for the procedure through description of the: microwaves rock interaction (heating phase), coolant rock interaction (cooling phase), and the mechanical reaction of the rock due to such sharp thermal variation. A 2D axisymmetric finite element model is used to demonstrate the procedure. The used rock is granite. A parametric study was conducted to illustrate the effects of coolant types on the damage evolution. The proposed mechanism is evaluated according to terms of: (1) the possibility of fracturing the rock, (2) reducing the energy required to fracture the rock (3) and penetration depth.

2. OUTLINES OF THE PROPOSED MECHANISM:

The proposed process is based on the Preston's description of the thermal spallation process with revolutionary modifications that hopefully make the difference in the field of thermal spallation drilling. However, the mechanism primarily depends on exploiting the ambushes of weakness of the rocks behavior; those will be the clues in diminishing the needs of energy to get the fragmentation of the rocks. While the Preston description (Preston et al,1934) depends only on inducing local compressive stress in the treated zones, we will try to topple these compressive stresses into tensile ones by rapidly and locally cooling down the previously heated zone. So the process will be subdivided in two phases.

The first is heating phase where the treated zone will be heated to certain limit at which the transition brittle-quasi brittle doesn't strongly occur yet. The microwaves will be used as heat radiation sources. The heat flux shouldn't be very intensive, that is to allow the temperature penetrates subsurface areas and consequently rock stocks heat energy and strongly expands relatively to surrounding non-treated zones. As well, the heat flux has to reach certain threshold to reach a maximum temperature strongly needed in the next phase to create a sharp descending temperature gradient. This sharp descending temperature gradient will serve in inversing the compressive stresses into tensile ones. In this stage, the treated zone will be completely compressed as described by Preston. Now a thermal differential dilatation between treated and non-treated zones was created. At certain limit, heating power will be cut off and immediately cooling phase will be started rapidly before that treated zone relaxes and loses the locally stocked energy during heating. Once the coolant (water, Air…) seeps on treated spot and according to the large difference between coolant temperature and surface one, very rapid energy dissipation will occur. Here, the treated zone strongly contracts and completely being charged by tensile stresses according to differential shrinkage between treated zone and non-treated zone that is also highly compressed in heating phase. The tensile stresses will increase over cooling time that is relatively short. Once tensile stresses overtake the rock tensile strength, the fracture takes place within the treated zone and its borders.

With time the system will search the equilibrium state between the coolant and treated surface. So then, gained tensile stresses will be neutralized according to the material's elasticity. Accordingly, at this moment the treated zone should be considered as removed part and then immediately another cycle of treatment will be lunched again. Here it is very important to adopt a damage constitutive law to evaluate this hypothesis which is out of present paper objective. Furthermore, the grown flaws (already existed in rock structure) by the heating will be a concentration point of the tensile stresses during cooling phase where the stress intensity factor at the tips of flaws will be proportional to the descendent temperature gradient (Lu et al,1998). As well during the heating phase the tensile strength of the rock will be negatively affected (Hommand-Etienne et al,1989), which will be a positive factor to efficiently remove out the treated zone.

The proposed mechanism depends entirely on three essential physical processes. The first is the interaction between the electromagnetic waves and the rock medium. We use the micro-waves frequency power as a radiation source, which is considerably cheap in operating and reported to be one of the destructive tools in crushing rocks or concrete demolishing (Jerby et al,2001). We considered the Lambert's expression that governs the impinged energy written as (Zhou et al,1995):

$$I_{(z)} = I_0 e^{-2.\alpha.z} \tag{1}$$

Where: I_0 and z are the incident power density and power penetration depth beneath the irradiated surface respectively. α Attenuation coefficient is expressed as a function of dielectric properties and the wave length of the waves:

$$\alpha = \frac{2\pi}{\lambda}.\sqrt{\frac{\varepsilon'.\left[(1+tg^2(\delta))^{\frac{1}{2}} - 1\right]}{2}} \tag{2}$$

$$tg(\delta) = \frac{\varepsilon''}{\varepsilon'} \tag{3}$$

ε' and ε" are the dielectric and loss dielectric of material. The Wavelength λ of micro-waves is 12.233 cm and the frequency is 2.45 GHz.

Heat transfer in the solids during both heating and cooling processes will be used, which is generally governed by the energy conservation equation:

$$\rho.C\frac{\partial T}{\partial t} = \nabla.(k.\nabla T) + Q \tag{4}$$

Where: T, ρ, C, k, t, Q are the temperature (°K),: density of the rock (kg/m^3), specific heat of the rock (J/kg.K), thermal conductivity of rock (W/m.K), time (sec), total heat sources (W/m^3), respectively. No change in the physical properties of the material with the temperature is considered.

Technically, cooling phase is the most important phase in whole procedure according to it the rock fracture will be produced. So to make this phase as efficient as possible, we have conducted a parametric study to choose the appropriate coolant that is potentially able to furnish rapid energy dissipation from rock body. This influence will appear through the heat convection coefficient h_c to enlarge the dissipated energy quantity. The heat flux during cooling phase will be calculated according to the next expression:

$$q = h_c .(T_{\inf} - T_s) \quad (5)$$

Where: $T_{inf,}$ T_s are the temperature of external fluid far from the boundary and surface temperature. The parametric study was done depending on values in Table 1.

Table 1. Heat convection coefficient values (Vlachopoulos et al,2002)

Type of coolant	W/m².K
Air free convection	4 to 28
Water free convection	300 to 1500
Air forced convection	4 to 570
Water forced convection	300 to 17000
Oil forced convection	50 to 2000
Boiling Water	3000 to 60000
Condensing Water vabor	5000 to 113000

In the mechanical aspect, we can distinguish between two parties, the first is during the heating process and the second is during the cooling one. Through the heating process, the treated zone will locally expand resulting in compressive stresses within the treated zone. These compressive stresses will overtake the threshold of the crack initiation reported as 30% of the compressive strength of granite (Vasconcelos et al,2008). Thus, the treated zone is initially damaged and the micro-cracks have been initiated. Once the heating process finishes and the cooling one is started, the treated zone will dramatically shrink because of the high energy dissipation rate. This shrinkage will be translated as tensile stresses within the treated zone. The previously initiated micro-cracks in the heating phase will be the concentration points of the tensile stresses. The levels of tensile stresses are not required to be as the same of the tensile strength where the damage induced in the heating phase will negatively influence the tensile strength of the rock as well as the compressive one. The reduction in the tensile strength reaches 33% of the intact rock strength (Hommand-Etienne et al,1989). This reduction is another auxiliary factor in the rock fracture process. Here for the first steps, the material is supposed to behave as isotropic linear elastic one where the model will be only concerned by the stresses' evolution during the whole process. So, the behavior is governed by the next expression:

$$\sigma_{ij} = C_{ijkl} .(\varepsilon_{kl} - \alpha \Delta T \delta_{kl}) \quad (6)$$

Where C_{ijkl} is the elastic modulus tensor, α is the thermal expansion coefficient, T temperature, δ_{kl} Kronecker delta. Figure 1 illustrates the whole process in order to get rock fracture.

3. NUMERICAL EXAMPLE:

The Granite rock is selected. Granite is thermally considered to behave as an isotropic material. The porosity of the granite is about 1% so we can neglect it. No variation in the properties of the granite is considered with the variation of temperature. The used granite properties are illustrated in Table 2. The heat convection coefficient h_c of the air that surrounds the sample is 10 $W/m^2.K$. The surrounding air temperature is 25 °C. The value of h_c during the cooling process is taken as 500 $W/m^2.K$ and 14000 $W/m^2.K$. Coolant temperature is chosen to be 40 °C. Mechanically the material behaves as isotropic- linear elastic one. The dielectric and loss dielectric factors are taken 5.753 and 0.1 respectively (Ulaby et al,1990). So the attenuation coefficient is 1.0785 (1/m). The model is implemented in 2D axisymmetric finite element environment COMSOL MULTIPHYSICS 4.2 interface. The sample is considered as cylinder of 40 mm as diameter and 40 mm of height. The treated zone has circular shape of radius 5 mm.

Table 2. Granite properties

Material properties	Density	Thermal conductivity	Specific heat	Thermal expansion coeff	Young Modulus	Piosson ratio
Granite	2600 ($Kg/m^{3)}$	1.8 (W/m.K)	930 (J/kg.K)	$7*10^{-6}$ (1/K)	60 (GPa)	0.25

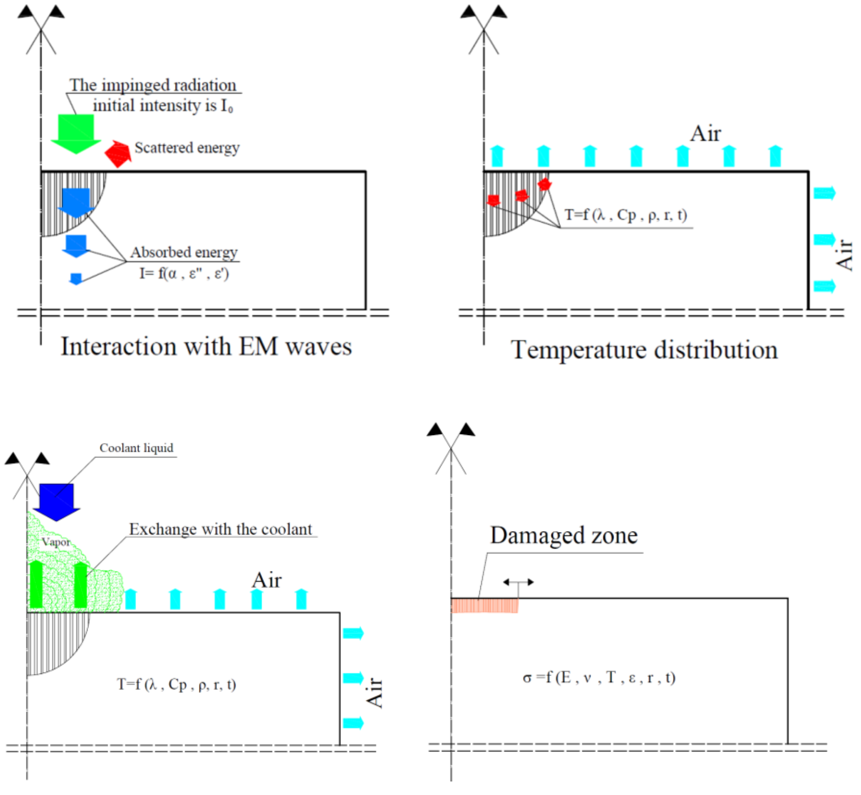


Figure 1: Illustration scheme of the proposed mechanism

4. RESULTS AND DISCUSSION:

The temperature variation with the time over the treated zone is shown in Figure 2. The maximal reached temperature is about 320 °C after 50 seconds of heating. Through the analysis we will focus on referential points in the temperature profile those are: (A) at the end of heating process, (B) after one second of cooling and (C) after four seconds of cooling. After the 50 seconds the temperature trends to be stable without an important increase. Once the cooling process is lunched, the temperature rapidly drops to reach (55 °C) after 1 second of cooling and temperature of the surrounding environment approximately after 10 seconds.

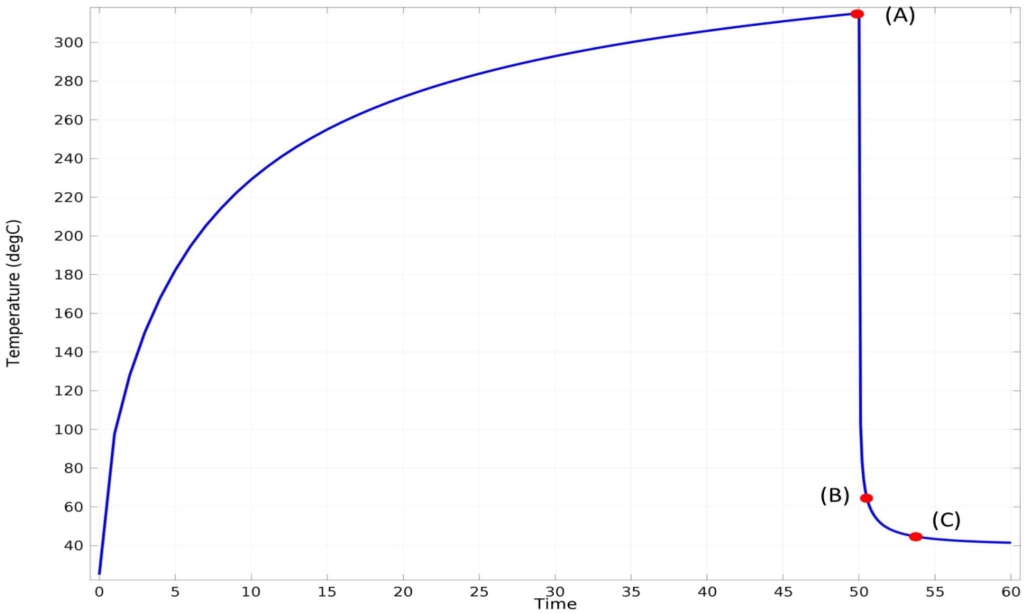
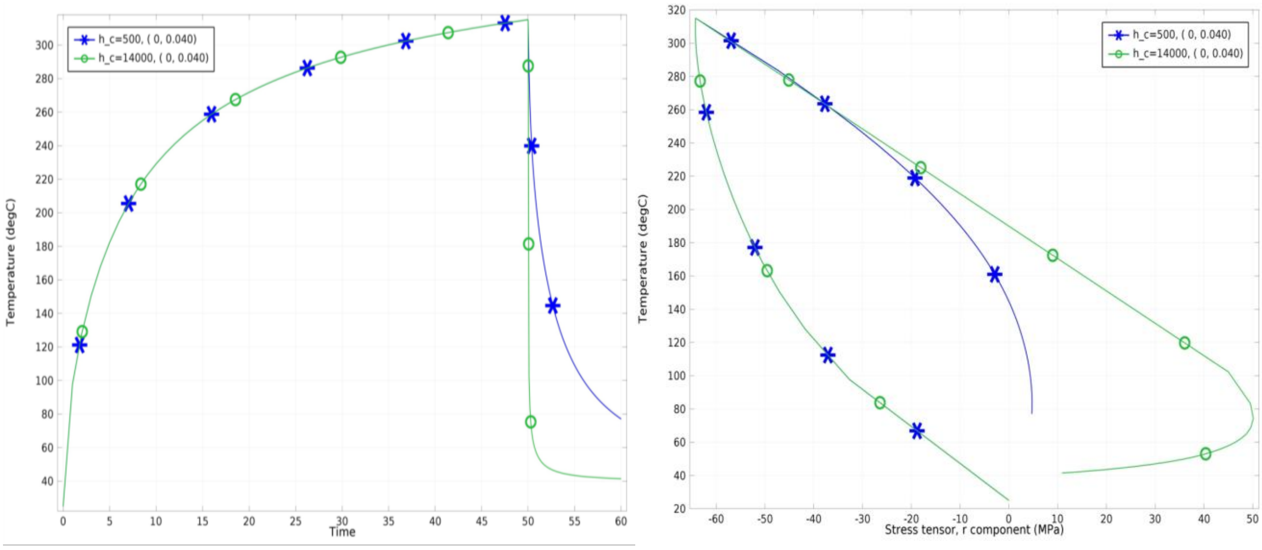


Figure 2: Temperature profile during whole process

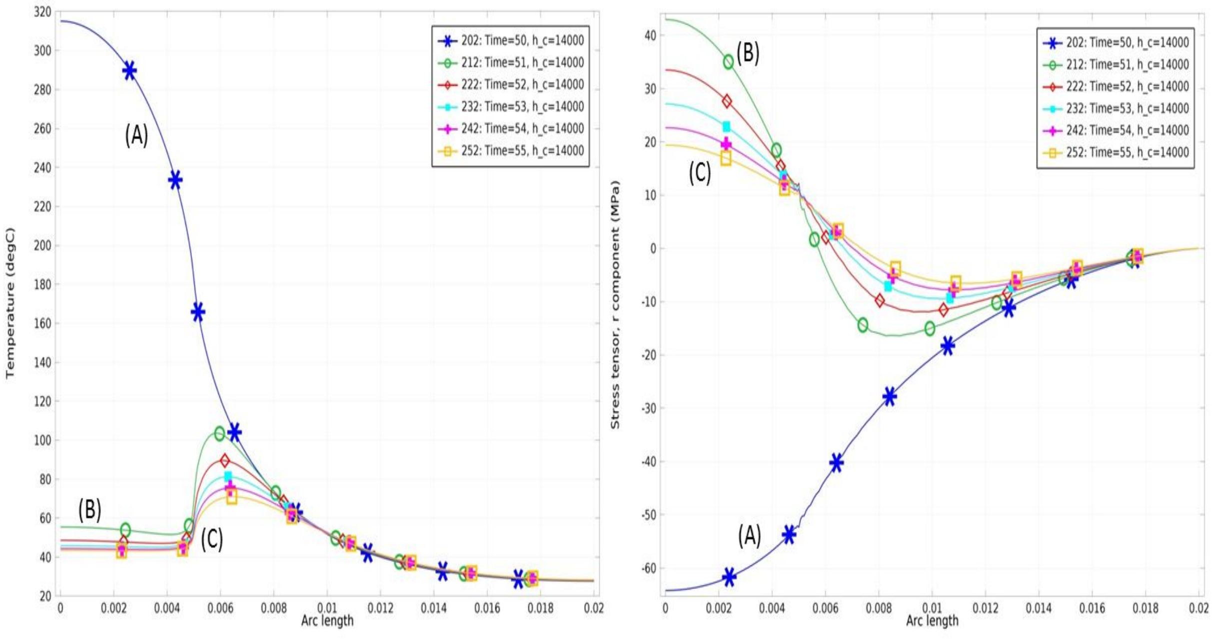
This rapid drop of temperature is strongly related to the coefficient of heat transfer h_c that determines the rapidity of energy dissipation. Figure 3 illustrates the influence of heat convection coefficient on the temperature profile and on the toppling process of stresses from compression to tension one.



(a) (b)

Figure 3: influence of heat convection coefficient on (a) temperature profile and (b) on stress evolution during the process

Apparently, the higher the value of heat convection coefficient, the efficient the cooling process is. The low value of h_c isn't able to inverse the compression stresses into tensile ones as desired to overtake the tensile strength of granite that is normally between (7~15 MPa). While high value of h_c strongly cools down the treated surface and efficiently induces high level tensile stresses. From mechanical point of view, during heating phase was totally compressed. Moreover as expected treated zone becomes completely charged by tensile stresses through cooling phase. Figure 4 (a) illustrates temperature variation along the radial distance of the sample through different moments of treatment. Figure 4 (b) shows the radial stress variation along the radial distance of the sample.



(a) (b)

Figure 4: (a) Temperature, (b) radial stresses along the radial distance of the sample

Through time, the tensile stresses degrade due to the elasticity of material and no more energy to be dissipated from the rock surface. The tensile stresses level is considerably high comparing to the reported tensile strength of granite. So that, we can consider that the failure took place in the subsurface areas in which the tensile stresses overtake the tensile strength. Figure 5 depicts the anticipated damaged area after 5 seconds of cooling if we use simple criteria that the tensile strength is considered equal to thermally affected tensile strength 6 (MPa). Here the importance of damage constitutive law is enormous to exactly expect the damage evolution after such treatment. Relating to the penetration depth, the proposed mechanism is able to penetrate the subsurface layers efficiently. The measured penetration depth is nearly 1mm.

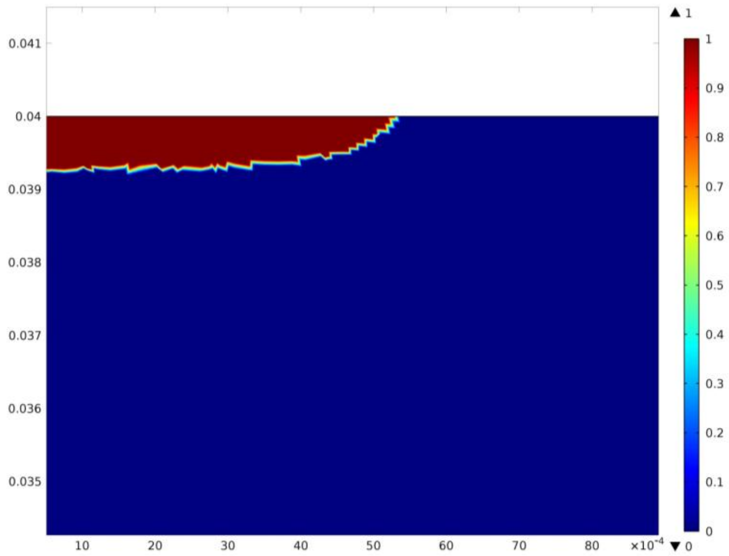


Figure 5: Expected damaged area

Concerning the power consumption, the maximal temperature is attained by using relatively small power intensity that is 0.15 MW/m². This power intensity is largely below the reported needed radiation intensity: 0.5~10 MW/m² (Rauenzahn et al,1989), 14.15 MW/m² (Xu et al,2005). It is clearly that the proposed mechanism numerically needs less amount of energy than the thermal spallation by heating only.

5. CONCLUSION:

A description of new methodology to thermally fracturing the rocky material was presented. The proposed mechanism combines rapid local heating and rapid local cooling to get rock fracture. Computationally, the suggested mechanism required less energy than the thermal spallation by heating according to the low energy density and the used materials (microwaves, water) terms. The proposed mechanism can really generate tensile stresses with values over the tensile strength of granite. Relating to the penetration depth the mechanism exhibits a reliable performance in reaching the same depth expected in heating spallation process under the treated surface. Prospectively, it is indispensable to establish a constitutive damage law to profoundly evaluate the mechanical damage evolution during the whole process.

REFERENCES

Ahmadi, M., Erfan, M.R., Torkamany, M.J., Sabbaghzadeh, J., The Effect of Confining Pressure on Specific Energy in Nd:Yag Laser Perforating of Rock, Optics & Laser Technology, **44**,(2012), 57-62.

Ahmadi, M., Erfan, M.R., Torkamany, M.J., Safian, G.A., The Effect of Interaction Time and Saturation of Rock on Specific Energy in Nd:Yag Laser Perforating, Optics & Laser Technology, **43**,(2011), 226-231.

Damhof, F., Brekelmans, W.A.M., Geers, M.G.D., Non-Local Modeling of Thermal Shock Damage in Refractory Materials, Engineering Fracture Mechanics, **75**,(2008), 4706-4720.

Hommand-Etienne, F., Hourpert, R., Thermally Induced Microcracking in Granite: Characterization and Analysis, International Journal of Rock Mechanics and Mining Sciences, **26**,(1989), 125-134.

Jerby, E., Dikhtyar, V., Drilling into Hard Non-Conductive Materials by Localized Microwave Radiation, in: Ampere Conference, Trends in Microwave and HF Heating, Springer Verlag, 2002, Bayreuth, Germany, 2001.

Lu, T.J., Fleck, N.A., The Thermal Shock Resistance of Solids, Acta Materialia, **46**,(1998), 4755-4768.

Olaleye B, M., A Review of Light Amplification by Stimulated Emission of Radiation in Oil and Gas Well Drilling, Mining Science and Technology (China), **20**,(2010), 752-757.

Preston, F.W., White, H.E., Observation on Spalling, Journal of the American Ceramic Society, **17**,(1934), 137-144.

Rauenzahn, R.M., Tester, J.W., Rock Failure Mechanisms of Flame-Jet Thermal Spallation Drilling - Theory and Experimental Testing, International Journal of Rock Mechanics and Mining Sciences, **26**,(1989), 381-399.

Ulaby, F., Bengal , T., Dobson, M.C., East, J., Garvin, J., Evans, D., Microwave Dielectric Properties of Rocks, in, University of Michigan, Michigan, 1990.

Vasconcelos, G., Lourenço, P.B., Experimental Characterization of the Compressive Behavior of Granites, Mecânica Experimental, **16**,(2008), 61-71.

Vlachopoulos, J., Strutt, D., Basic Heat Transfer and Some Application in Polymer Processing, in: Plastics Technician's Toolbox, 2002, pp. 21-33.

Xu, Z., Reed, C.B., Graves, R., Parker, R., Rock Perforation by Pulsed Nd:Yag Laser, in: International Congress on Applications of Lasers and Electro-Optics, 2004.

Xu, Z., Reed, C.B., Parker, R., Graves, R., Laser Spallation of Rocks for Oil Well Drilling, in: International Congress on Applications of Lasers and Electro-Optics, 2004.

Xu, Z., Yamashita, Y., Reed, C.B., Two Dimensional Modelling of Laser Spallation Drilling of Rock, in: International Congress on Applications of Lasers and Electro-Optics, ICALEO, Laser Institute of America 2005.

Zhou, L., Puri, V.M., Anantheswaranb, R.C., Yeh, G., Finite Element Modeling of Heat and Mass Transfer in Food Materials During Microwave Heating - Model Development and Validation, Journal of Food Engineering, **25**,(1995), 509-529.