International Journal of Heat and Mass Transfer 65 (2013) 366–373

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Micromechanical modeling of thermal spallation in granitic rock

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ARTICLE INFO

*Article history:*
Received 29 December 2012
Received in revised form 23 April 2013
Accepted 16 May 2013
Available online 8 July 2013

*Keywords:*
Thermal spallation
Numerical simulation
Micromechanical modeling

ABSTRACT

While the underlying mechanisms governing thermal spallation in rock have been known since the 1930s, our ability to model this behavior remains largely empirical. Leading models of thermal spallation either rely on experimentally derived relationships linking applied thermal stresses to spall production, or employ idealized representations that ignore the effects of rock microstructure. Although such models are useful for describing systems within a given context, they are less suited to extrapolate outside the range to which they are fitted or to derive new insight into how mechanisms at smaller-scales influence spall production.

This paper describes a numerical modeling tool designed to conduct explicit simulations of thermal spallation at the grain-scale. The model uses an Eulerian–Godunov scheme to simulate solid and fluid mechanical behavior, permitting both inter- and intra-granular fracture. Simulations conducted with the model illustrate how differences in rock properties, microstructural geometry and mineral volume fractions, combined with variations in thermal and mechanical loading conditions, influence spallation at the grain scale. We discuss the implications of these results on the processes controlling thermal spallation of rock, in particular, the role of micropores in the onset and extent of spallation.



## 1. Introduction

Rapid heating of certain rock-types causes thin disk-like fragments or "spalls" to be removed from the surface in a process known as thermal spallation. Thermal spallation in rock is widely regarded to follow a mechanism first described in the 1920s and 1930s [1,2]. Due to the rock's low thermal conductivity, heating produces large temperature gradients and associated compressive stresses close to the surface. The compressive stresses cause fractures to emanate from pre-existing flaws. The fractures extend outward parallel to the rock surface, following the principle compressive stresses. If an induced fracture propagates to a sufficient extent, the heated fragment buckles and is ejected as a spall (Fig. 1). Thermal spallation has long been of interest as a means of achieving faster penetration compared to conventional mechanical drilling methods, particularly for brittle granitic rocks [3–5]. Applications include blast hole drilling, quarrying, deep-well drilling, cavity formation and well stimulation [6,7,5,8,9]. Fire-induced spallation of rock has also been identified as a growing concern in tunnel and mine safety [10–13].

At present, models of spall production remain largely empirical in nature or adopt simplifying assumptions that ignore microstructural heterogeneity. For example, several analytical models have been developed based on buckling theory [e.g.][14,15]. The advantage of these models is that they present a closed-form solution that can be rapidly evaluated. However, for the most part such models assume a homogeneous material body, making it difficult to predict changes in the spallability of different rock types. To overcome these limitations, researchers examining thermal spallation in granitic rocks have employed Weibull statistical failure theory [16] to represent the relationship between microstructural heterogeneity and the rock's propensity to spall [17–20]. Such Weibull models have been successfully used to predict such factors as penetration rate, spall-size distribution and borehole radius from drilling jet velocity and applied heat flux [19,20].

Nevertheless, although useful for predicting system response in a given context, Weibull models are empirically derived. As such, the model parameters must be carefully fitted from laboratory tests. Moreover, such models may overlook material behavior outside of model assumptions. For example, while Weibull models of spallation postulate the existence of a distribution of critical flaws, they make no claims to the nature of these flaws or how the distribution should change according to rock composition. Consequently, it can be difficult to determine how these models should behave outside the experimental scope from which they are fitted. Indeed for many applications (*e.g.* thermal spallation drilling) it may be prohibitively expensive to conduct appropriate experimental investigation under the appropriate conditions or impossible to obtain the relevant experimental data. In such an

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0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.05.043

**Nomenclature**

| | | | |
|---|---|---|---|
| $\beta_\alpha$ | pressure update limiter | $p_\alpha$ | pressure in material $\alpha$ |
| $\Delta t$ | timestep duration | $S_H$ | source operator |
| $\epsilon_f$ | strain to failure | $S_{i_\beta,j_\beta,k_\beta}$ | spatially split operators for each axis |
| $\epsilon_p$ | plastic strain | $t$ | time |
| $\lambda$ | mixed material thermal conductivity | $T_{ij\alpha}$ | stress tensor of material $\alpha$ |
| $\lambda_\alpha$ | thermal conductivity of material $\alpha$ | $T_{ij}$ | mixed material stress tensor |
| $\phi_\alpha$ | volume fraction of material $\alpha$ | $U^{n,H}_{i,\alpha}$ | state vector after three consecutive 1D sweep operations |
| $\rho$ | density | $U^{n}_{i,\alpha}$ | vector of state and internal variables for material $\alpha$ at timestep $n$ |
| $\Theta$ | Temperature | $\mathbf{L}$ | mixed material velocity gradient |
| $c$ | cohesion | $\mathbf{L}_\alpha$ | velocity gradient for material $\alpha$ |
| $c_o$ | undamaged cohesion | $\boldsymbol{q}$ | heat flux |
| $D$ | damage | $\mathbf{v}$ | velocity |
| $F_i$ | history dependent state and internal variables | $\mathbf{V}$ | Voronoi cell volumes |
| $G$ | mixed material shear modulus | $\mathbf{V_{target}}$ | target Voronoi cell volumes |
| $G_\alpha$ | shear modulus of material $\alpha$ | $\mathbf{X}$ | Voronoi cell centers |
| $H_\alpha$ | source term for material $\alpha$ | | |
| $K$ | mixed material bulk modulus | | |
| $K_\alpha$ | bulk modulus of material $\alpha$ | | |
| $p$ | average pressure | | |

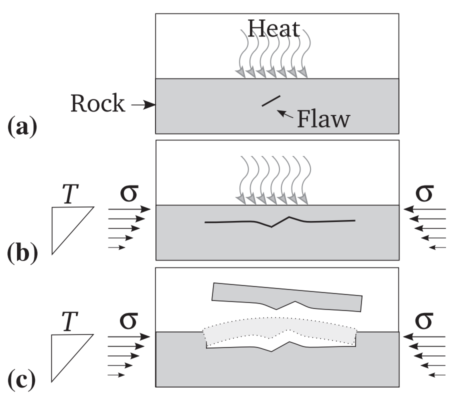


**Fig. 1.** Spall-production model proposed by Preston [1,2]: (a) An applied heat flux increases the temperature of the rock face, increasing the compressive stresses adjacent to the surface. (b) The compressive stresses cause fractures to grow parallel to the surface from incipient flaws in the rock. (c) Upon reaching a critical size, the heated region buckles and is ejected from the surface as a spall.

environment, explicit small-scale numerical simulations can be used to provide insight into the fundamental processes contributing to thermal spallation.

In this paper, we outline a numerical modeling effort investigating the grain-scale mechanics of thermal spallation. We describe the numerical simulator used to run the model, and the material parameters employed in the simulations – including the process by which the rock microstructure is generated. Results from simulations conducted with the model are also presented, illustrating how differences in rock properties, microstructural geometry and mineral volume fractions, combined with variations in thermal and mechanical loading conditions, influence spallation in rocks. We discuss what these results reveal about the processes driving spallation at the grain-scale, in particular, the role of micro-porosity in the onset and extent of spallation.

## 2. Model description

The models presented in this paper are conducted using the geomechanical simulator, GEODYN, developed at Lawrence Livermore National Laboratory. GEODYN is a parallel Eulerian compressible-solid and fluid-dynamics code with adaptive mesh refinement (AMR) capabilities [21,22]. Its features include a high-order material interface reconstruction algorithm [23] and advanced constitutive models that incorporate salient features of the dynamic response of geologic media [24]. GEODYN is able to simulate materials under extremely large deformations and resolve details of wave propagation within grains with high accuracy. Moreover, as it employs a continuum damage mechanics approach to represent fracturing, it is able to simulate fracture propagation within grains. This modeling capability is necessary, as spalls are disk-like in shape; often one or-more grain-diameters in extent with thicknesses below a single grain diameter [25,7].

The Eulerian–Godunov method implemented in GEODYN is a modified version of a single-phase high-order Godunov method that has been extended to track multiple material bodies [26]. For solid materials, the governing equations consist of the laws of conservation of mass, momentum and energy, an equation for elastic deformation, and additional equations in the form:

$$\frac{\partial}{\partial t}(\rho F_i) + \nabla \cdot (\rho \mathbf{v} F_i) = \rho \Phi_i, \tag{1}$$

which represent specific rheological equations $\dot{F}_i = \Phi_i$ (superposed dot denotes material time differentiation) for history dependent state and internal variables $F_i$ (damage, plastic strain, etc.).

Propagation of surfaces in space is similarly modeled via an equivalent evolution of volume fractions, defined by:

$$\frac{\partial \phi_\alpha}{\partial t} + \nabla \cdot (\phi_\alpha \mathbf{v}) = \frac{\phi_\alpha}{K_\alpha} K \nabla \cdot \mathbf{v}, \tag{2}$$

where $\phi_\alpha$ and $K_\alpha$ are the volume fraction and the bulk modulus of each material $\alpha$.

The numerical scheme for a single cell is based on the approach of [27], with modifications to account for the full stress tensor associated with solids. The multidimensional equations are solved by using an operator splitting technique, in which the one-dimensional equations for each direction are solved:

$$U^{n+1}_{i,\alpha} = S_H\left(S_{1,0,0}\left(S_{0,1,0}\left(S_{0,0,1}\left(U^{n}_{i,\alpha}\right)\right)\right)\right), \tag{3}$$

$$U^{n+2}_{i,\alpha} = S_H\left(S_{0,0,1}\left(S_{0,1,0}\left(S_{1,0,0}\left(U^{n+1}_{i,\alpha}\right)\right)\right)\right), \tag{4}$$

where the spatially split operators