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Technical Note

Size dependent spall aspect ratio and its effects in thermal spallation

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1. Introduction

Rapid heating of certain rock types results in thermal spallation: a process in which small particles are ejected from the rock surface [1,2]. As a result of the rock's low thermal conductivity, large temperature gradients and associated compressive stresses are produced in the rock immediately adjacent to the heated face. The compressive stresses, in combination with vapor pressure from the expansion of trapped pore fluids [3,4], cause fractures to grow from pre-existing flaws. The propagating fractures follow the direction of the principle compressive stresses, parallel to the rock surface, eventually resulting in the liberation of disk-like spall fragments (Fig. 1).

Thermal spallation is of particular interest for drilling and mining applications, as it provides a mechanism for achieving faster penetration of hard granitic rocks than traditional mechanical means [5–9]. Moreover, because it is a contactless method, wear on the drill-bit is reduced, as is time lost through "tripping" or bit replacement. This has lead to a proliferation of different thermal spallation drilling methods distinguished by the mechanisms used to heat the rock face. Examples include flame-jet, hydrothermal, laser and plasma spallation, to name but a few [10–15,7]. In addition to potential drilling and mining applications, thermal spallation is also of interest in areas related to tunnel and mine fire safety. Although the principle focus in this area has been on the failure of high performance cements, the high temperatures and rapid heating involved can also result in spallation of exposed rock [16–19].

Despite interest in thermal spallation in a number of areas, current large-scale models of spall production remain empirical in nature. This is most likely a consequence of the large range of spatial and temporal scales involved. Spall production is triggered by the initiation and sudden growth of fractures driven by sub-grain scale processes on sub-second timescales. Yet industrial applications require macroscale models capable of capturing the effects of spallation at scales of meters and hours. As a consequence, researchers examining thermal spallation in granitic rocks have employed a variety of different approaches to represent the rock's propensity to spall [20–25]. In particular, models based on Weibull statistical failure theory [26,21] have been successfully used to predict factors such as penetration rate, spall-size distribution and borehole radius from drilling jet velocity and applied heat flux [23,24]. Nevertheless, despite these successes, the empirical nature of these models implies that material behavior may be overlooked when outside the scope of the model assumptions.

An important assumption adopted in many large scale spallation models (including Weibull-type models) is that spalls are produced with a constant aspect ratio independent of the spall size. In this paper, we test this assumption by examining particles collected from a thermal spallation drilling field test, as well as through high-fidelity numerical simulations of thermal spallation at the grain scale. Both the simulated spalls and the collected field-test particles have size-dependent aspect ratios – exhibiting more equant shape at smaller sizes. To illustrate what impact this finding may have on large-scale models, we demonstrate how a size-dependent aspect ratio can be incorporated into Weibull models of spall production, and discuss its effect on the relationship between the rate of penetration, applied heat flux and surface temperature. The variable spall-aspect ratio is found to be most influential at higher rates of penetration as the length scale associated with the advancing heat front approaches a transition in the spall aspect ratio.

2. Experimental and numerical methods

The spall particles examined in this paper were gathered from a field test conducted in Sierra white granite at the Potter-Drilling

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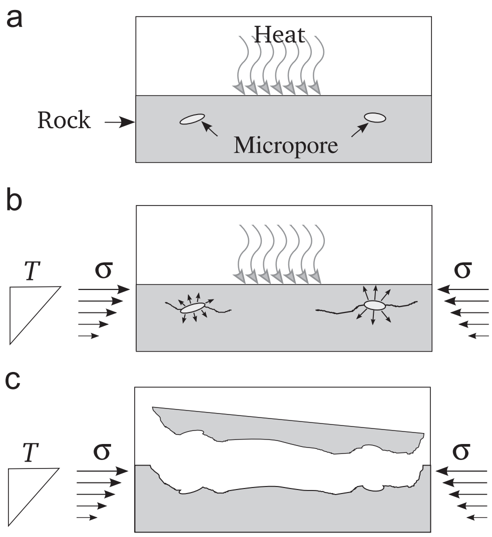

Fig. 1. Stages in spall production: (a) an applied heat flux increases the temperature of the rock face, increasing compressive stresses immediately adjacent to the surface. (b) The compressive stresses cause fractures to grow parallel to the surface from incipient flaws in the rock, and the expansion of fluid within the pores aids in fracture propagation. (c) The heated region is ejected from the surface as a spall.

test site near the town of Raymond, CA. The spalls were collected during a demonstration of a thermal spallation slotting technology – a hole expansion technique designed to improve the hydraulic characteristics of geothermal wells. The field test was conducted in a pre-existing 4–5 in. borehole using a hydrothermal spallation drill (i.e. one in which a superheated water jet provides the heat source for spallation). The drill bit was 3.5 in. in diameter and capable of delivering 70 g/s of fluid flow at temperatures up to 1000 °C. The spall particles produced during the field-test were collected from a depth of 300 ft. After collection the particles were sorted by size into six categories: extremely large spalls (over 0.5 cm in size); spalls greater than 2000 μm in size; spalls between 1400 and 2000 μm; spalls between 850 and 1400 μm; spalls between 300 and 850 μm; and spalls below 300 μm in size. Additional details concerning the field study and the thermal-spallation slotting technology employed are provided in [9].

The explicit grain-scale simulations were 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 [27,28]. Its features include a high-order material interface reconstruction algorithm [29] and advanced constitutive models specifically designed to capture the dynamic response of geologic media [30]. GEODYN is able to simulate extremely large deformations and resolve details of wave propagation to high accuracy. As it employs a continuum damage mechanics approach to represent fracturing, GEODYN is able to simulate fracture propagation within grains. This modeling capability is necessary, as spalls are often one or more grain-diameters in extent but with thicknesses below a single grain diameter [31,6]. The Eulerian–Godunov method implemented in GEODYN is a modified version of a single-phase Godunov method that has been extended to track multiple material bodies. This allows minerals with distinct material properties to be assigned to each grain in the assembly, as well as separate fluid components with distinct constitutive models. Grain microstructures consisting of quartz, plagioclase feldspar and potassium feldspar (K-spar) were used for the simulations discussed here. The mechanical parameters used in the simulations are taken from [32,33], while the heat capacities and relative thermal conductivities are based on values reported in [34–36]. The rock microstructures employed in the simulations are created by fitting the cells in a Voronoi tessellation to specific grain-size distributions. Voronoi cells are generated from a set of random points, each cell is assigned a target volume, and the system is iteratively relaxed towards the target distribution until the average error in cell volumes is below a predetermined tolerance (typically less than 1% error in cell volumes). In this manner, separate grain-size distributions may be set according to the mineral type, or even on a grain-by-grain basis. The GEODYN code and the methods used to generate the initial granite microstructure are described in greater detail in [4].

3. Aspect ratio and spall size

An assumption commonly employed in continuum models of spall damage is that idealized disk shaped spalls are produced with a constant ratio of spall thickness to particle radius. Results from the numerical simulations, along with observations of spalls collected from field and laboratory tests, however, suggest that the aspect ratio is in fact dependent on the spall size. Changes to the spall aspect ratio are influenced by microstructural heterogeneity, particularly as the spall particle size approaches, or falls below, that of individual mineral grains. This is important as in many cases the modal spall diameter is less than one millimeter, as indicated in Fig. 2 which shows a typical spall particle size distribution collected from a laboratory test conducted by Potter Drilling.

To investigate the distribution of spall aspect ratios further, a study was conducted examining changes to spall thickness as a function of the cross-sectional area. Digital images of the spalls were obtained under a microscope with both angled and diffuse light sources, and image analysis was conducted to extract the shadow dimensions (Fig. 3). The feature heights were determined from the shadow extents by calibrating against the shadow of a silicon wafer of known thickness, while the shadow lengths perpendicular to the lighting direction were used to determine the in-plane width of each spall particle (Fig. 3b).

The spall sizes and thicknesses obtained from the angled-light images are plotted in Fig. 4a, and the aspect ratio (size/thickness) for the spalls is given in Fig. 4b. The larger spalls examined in the analysis exhibit aspect ratios between 4:1 and 10:1 diameter to thickness. This is slightly smaller than the previous reported aspect ratios from experiments (between 8:1 and 15:1 [37]) and estimates based on plate and beam buckling theories (which predict ratios between 10:1 and 15:1 [21]). In part, the smaller aspect ratios observed in this study are a product of the manner in which the measurements were collected. As here the focus has

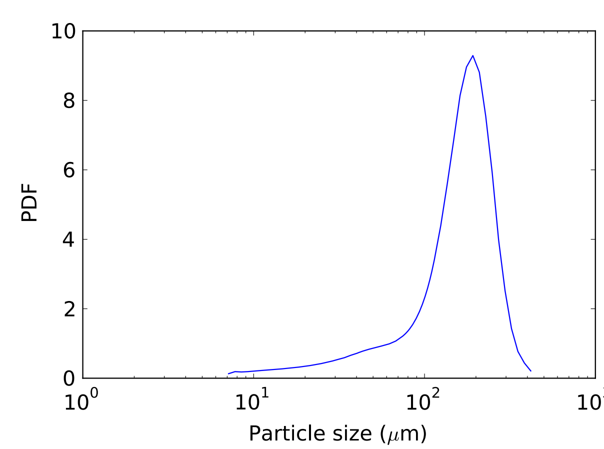

Fig. 2. Spall size distribution collected from a laboratory test of thermal spallation drilling into granite by Potter Drilling.