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Minimal required boundary conditions for the thermal spallation process of granitic rocks

Michael A. Kant, Philipp Rudolf von Rohr*

ETH Zurich, Institute of Process Engineering, Sonneggstrasse 3, 8092 Zurich, Switzerland

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ABSTRACT

The spallation process is based on the effect, that hard rocks with a high quartz content disintegrate into small disc-like fragments, if the rock surface is rapidly exposed to high thermal loads. Spallation is pursued as a contact-free drilling technology for various applications. In view of increasing the knowledge about the process and for determining the limitations of the applicable operating range, a profound knowledge of the minimal required boundary conditions are of significant importance. These conditions are characterized by the lowest surface temperature and heat transfer coefficient at which spallation can be successfully initiated. In order to determine the minimal required boundary conditions, spallation experiments were conducted in which granitic rock samples were rapidly heated by a methane–air burner. A novel measuring concept is proposed to measure the surface temperature, using high-speed pyrometers to temporally resolve the detachment of single spalls. The heat transfer coefficient of the impinging flame was determined by measuring the heat flux in the stagnation point of the jet using an industrial heat flux sensor. The reported data of the boundary conditions show good accordance with data published by other researches and supports their proposed characteristic for the specific heating process.

1. Introduction

If certain rock types are rapidly exposed to a hot fluid jet, the upper layer of the rock will locally disintegrate into small disc-like fragments. This so-called spallation effect can be used as a contact-free drilling technology for various applications.[1–3] Additionally, spalling of rocks and concrete came recently into the focus of research on fire in tunnels.[4–6] During the spallation process, a high heat flux is transferred from the impinging hot fluid jet to the rock. Thereby, due to the low thermal conductivity of the rock, high surface temperatures are induced, leading to high thermal stresses in the upper layer of the rock. Moreover, the cold surrounding rock acts as a confinement and produces compressive stresses on the local failure zone. Due to the thermally induced stress field, the rock will locally disintegrate at naturally present flaws into small fragments called spalls (see Fig. 1).[3,7] The created spall buckles when losing the contact in the failure plane. Finally, as a result of tensile stresses at the outside of the spall, the hot spall is ejected from the surface and the spallation process continues on with the newly exposed rock surface. Thereby, the spallability will vary considerably within different rock types: hard rocks are easier to spall than soft, sedimentary rocks.[8–11] The spallation effect has been investigated by several researchers.[1–3,7,12–14] Nevertheless, the lowest boundary conditions where spallation can be initiated were so far not systematically analyzed.

1.1. Boundary conditions for spallation

Two main parameters for the required boundary conditions for the spallation process are reported so far: the heat flux q through the rock respectively the heat transfer coefficient h_{fl} between rock surface and impinging fluid jet and the induced spallation temperature ϑ_{SP} of the rock [11-14]. The spallation temperature ϑ_{SP} is defined as the surface temperature directly before the spall detaches from the surface. Right after the spall is ejected from the surface, the temperature in the failure plane of the spall ϑ_{FP} can be measured. The occurring temperature difference $\Delta\vartheta = \vartheta_{SP} - \vartheta_{FP}$ between these two temperatures is an important parameter for the investigation of the spallation process.

In several publications, measurements of the boundary conditions in spallation experiments are reported.[13,14] These reports are based on the determination of the spallation temperature ϑ_{SP} and the heat flux q through the rock. In order to improve these measurements, Wilkinson [14] and other researchers proposed to use high-speed pyrometers for future measurements, which are

* Corresponding author.
E-mail addresses: kant@ipe.mavt.ethz.ch (M.A. Kant), vonrohr@ipe.mavt.ethz.ch (P. Rudolf von Rohr).
URL: http://www.ltr.ethz.ch (M.A. Kant).

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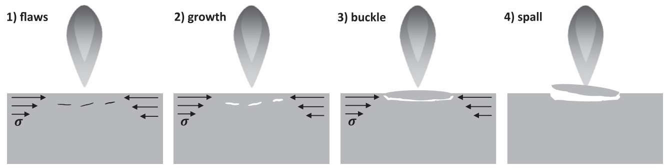

Fig. 1. Illustration of the spall formation on the rock surface, adapted from [7].

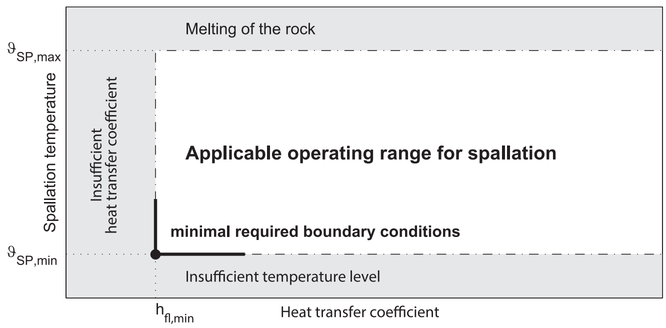

Fig. 2. Illustration of the boundary conditions limitations for the successful application of the spallation process.

able to resolve the spallation process. Therewith, an exact differentiation between spallation temperature ϑ_{SP} and temperature in the failure plane ϑ_{FP} is possible.

Apart from these experiments, different models based on theoretical and empirical approaches were developed to describe the effect of spallation and the appearing boundary conditions. Reviews about these models can be found in [2,15,10]. Thereby, the model developed by Rauenzahn [13], which uses Weibull's statistical theory of brittle failure, has to be particularly highlighted. Nevertheless, the spallation effect occurs at rates and scales and in rock environments that are difficult to experimentally probe.

Generally, by increasing the heat flux through the upper layer of the rock, the spallation frequency will increase and the thickness of the spalls will decrease.[13] On the other hand, the spallation temperature has to be kept under the melting point, which states the upper limit $\vartheta_{SP,max}$ of the boundary conditions range where spallation is applicable (see Fig. 2). Similar to this, a lower limit exists for the appearance of the spallation process. These minimal required boundary conditions are characterized by the lowest spallation temperature $\vartheta_{SP,min}$ and heat transfer coefficient $h_{fl,min}$ where spallation can be successfully initiated. Additionally, these conditions specify the size of the operating window where spallation can be utilized. In this report, the minimal required boundary conditions were defined as the conditions where at least a single spall could be detected by the measuring devices. Under this lower limit, the required heat transfer coefficients and surface temperatures are not reached and so the rock will heat up too slowly and no steep temperature gradient is created inside the rock, which will inhibit the spallation process, as only insufficient thermal stresses are created.

The optimal boundary conditions for spallation, where the highest spall performance can be achieved, will lie in between these two bounds.

Concluding, the minimal required boundary conditions define the lower limitation of the applicable operating range for spallation (see Fig. 2). Therewith, they can be used as boundary conditions for theoretical simulations of the spallation process and modeling approaches (e.g. failure mode determination, crack growth simulations, and grain scale failure analysis). Furthermore, they define the required operating conditions for spallation tools, as they specify appropriate flame temperatures and jet velocities. In order to optimize the application and to enhance the understanding of the process, both the upper and lower boundary condition limits have to be known. As the melting point is a property of the rock type and has been widely studied in the literature, this report focuses on the lower boundary condition limit, which is still poorly investigated.

To this aim, rock samples of Gotthard Granite (Gurtnellen, Switzerland) and Bethel Granite (Bethel, Vermont, USA) were rapidly heated by a methane–air burner. The spallation temperature was measured using high-speed pyrometers. With this setup the disintegration of single spalls could be monitored as well as the difference between spallation temperature ϑ_{SP} and temperature in the failure plane ϑ_{FP}. As the pyrometer can temporally resolve the spallation process, the proposed measuring concept could contribute to the fundamental understanding of the spallation process. The heat transfer coefficient h_{fl} (W/(m^2 K)) was determined by measuring the heat flux q_{sens} (W/m^2) in the stagnation point of the impinging flame jet with an industrial heat flux sensor along with the fluid temperature ϑ_f and the surface temperature of the sensor $\vartheta_{s,sens}$ both in °C:

$$h_{fl} = \frac{q_{sens}}{\vartheta_f - \vartheta_{s,sens}} \tag{1}$$

2. Material and methods

In order to determine the boundary conditions during the spallation process, adequate measuring devices and an appropriate setup is required. Therefore, two different experimental setups for conducting the spallation experiments (determination of ϑ_{FP} and ϑ_{SP}) and for measuring the heat transfer coefficient h_{fl} are introduced in the following section. Additionally, in order to enhance the reliability of the reported values an error estimation was conducted.

2.1. Spallation experiments and infrared surface temperature measurements

2.1.1. Experimental setup

The required flame jet to induce spallation is supplied by a 10 kW methane–air burner (Pharos E-354, see Fig. 3). The air and methane flow is controlled by mass flow controllers (Bronkhorst

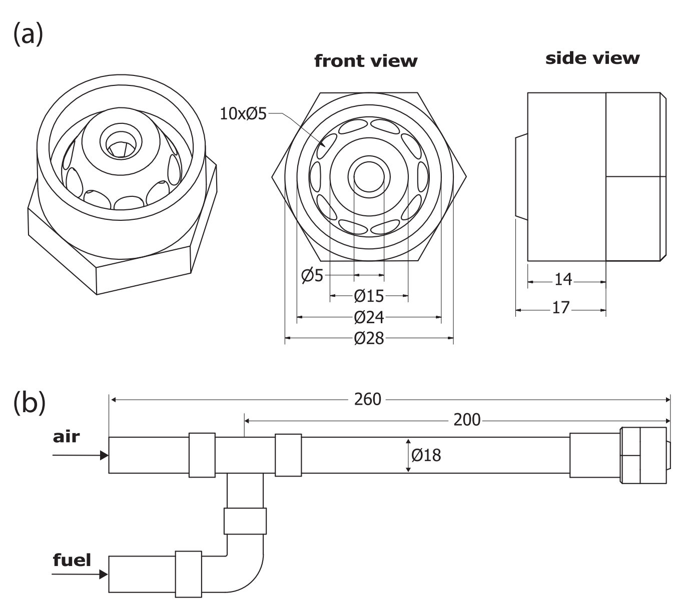

Fig. 3. (a) Schematic drawing of the nozzle with the most important dimensions. (b) Illustration of the burner assembly; dimensions in mm.