Characterization of mechanical damage in granite

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ABSTRACT. This paper aims to illustrate the use of infrared thermography as a non-destructive and non-contact technique to observe the phenomenological manifestation of damage in granite under unconfined compression. It allows records and observations in real time of heat patterns produced by the dissipation of energy generated by plasticity. The experimental results show that this technique, which couples mechanical and thermal energy, can be used for illustrating the onset of damage mechanism by stress concentration in weakness zones.

KEYWORDS. Differential thermography; Intrinsic dissipation; Mechanical damage in granite; Threshold of acceptable damage.

INTRODUCTION

Current technological developments tend towards increased exploitation of material strengths and towards tackling extreme loads and environmental actions. The tendency to extend the service life of materials and structures by increasing maintenance, rather than replacement, increases the need for monitoring structures and supports the need to perform global or local test loading. Diverse damage analysis methodologies for engineering materials have been developed in recent years which isolate the factors affecting crack initiation and growth, and enable the prediction of their cumulative effects on the fatigue performance of structural components [1]. In cases where continuum mechanics can be applied, the concept of an effective stress $\sigma_{ef} = \sigma/(1-\delta)$ has been introduced with a continuous variable δ related to the scalar density of defects or faults. This has been the starting point of damage theories developed for fatigue, creep, and creep-fatigue interaction in engineering materials.

Brittle geomaterials are mainly characterized by their salient fracturing nature. A different approach has been proposed using the plasticity formalism with the concept of a fracturing stress (considered hereafter as a threshold of acceptable damage TAD) or a fracturing strain to describe the inelastic behavior of progressively fracturing solids [2]. Failure in brittle geomaterial may be viewed as a micro-structural process through the activation and growth of one pre-existing flaw or site of weakness, or through the coalescence of a system of interacting small flaws and growing micro-cracks [3]. The formation of micro-cracks are often associated with points of stress concentration that are located on flaws present in the material, or on existing cracks and notches.

Several scientific studies have been carried out in recent years on the infrared radiation in the process of rock deformation leading to fracturing and failure [4-6]. Within the framework of a consistent theoretical approach, this paper emphasizes the application and use of infrared thermography to detect and evaluate quantitatively the extent of damage in brittle geomaterials owing to the non-linear coupled thermomechanical effects.

BACKGROUND OF THERMOMECHANICAL COUPLING IN SOLIDS

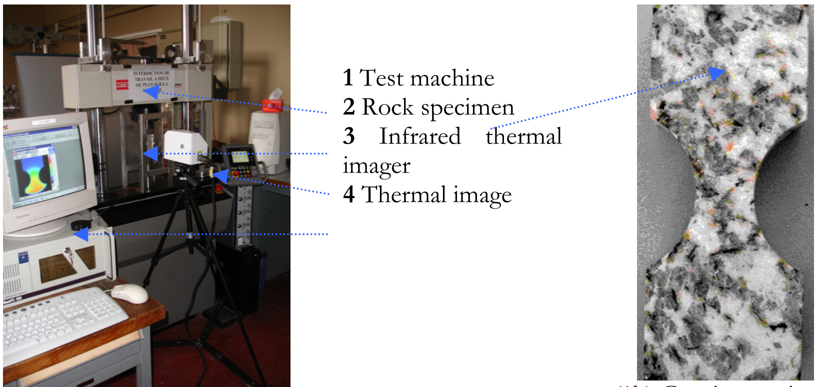
The development of the thermo-elastic- plasticity governing equations [7] leads to the following coupled thermomechanical equation:

$$\rho\, C_v\, \theta_{,t} = \rho r + \mathrm{div}\,(k\ \mathrm{grad}\theta) - (\beta : D : E^e_{,t})\ \theta + S : E^I_{,t} \qquad (1)$$

where ρ ($kg^{-1}.m^{-3}$) denotes the mass density, C_V ($J.kg^{-1}.K^{-1}$) the specific heat at constant deformation, $\theta_{,t}$ ($K.sec^{-1}$) the time derivative of the absolute temperature, r the heat sources, div the divergence operator, k ($W.m^{-1}.K^{-1}$) the thermal conductivity, grad the gradient operator, β (K^{-1}) the coefficient of the thermal expansion matrix, **:** the scalar product operator, D the fourth-order elastic stiffness tensor, $E^e_{,t}$ the time derivative of the elastic strain tensor, S the second Piola-Kirchhoff stress tensor and finally E^I the inelastic strain tensor. The volumetric heat capacity $C = \rho\, C_v$ of the material is the energy required to raise the temperature of a unit volume by 1°C (or 1 Kelvin).
This coupled thermomechanical equation suggests the potential applications of the infrared scanning technique in diverse engineering domains [8-10]: detection of fluid leakage, non-destructive testing using thermal conduction phenomena, elastic stress measurements, and localization of dissipative phenomena. Thus the detected temperature change, resulting from four quite distinctive phenomena (heat sources, thermal conduction, thermo-elasticity and intrinsic dissipation), must be correctly discriminated by particular test conditions and/or specific data reduction. This analysis is the principal difficulty when interpreting the thermal images obtained from experiments under the usual conditions.

INFRARED THERMOGRAPHY

Infrared thermography allows imaging and measuring temperature from radiation in the infrared spectral band. In this paper the infrared imaging system utilizes an infrared focal plane camera operating in MWIR wavelength band (mid-wave infrared window from 3 to 5 μm) and in snap shot mode of image capture. The infrared detector converts the emitted radiation into electrical signals that are recorded and displayed on a color or black & white computer monitor. Since infrared radiation is emitted by all objects according to the black body radiation law, the amount of radiation emitted by an object increases with temperature, thermography allows the detections of variations in temperature. The quantity of energy emitted as infrared radiation is a function of the temperature and the emissivity of the specimen according to the Stefan-Boltzman equation. The higher the temperature, the more important is the emitted energy. Differences of radiated energy reflect temperature differences.



(1a) Testing equipment

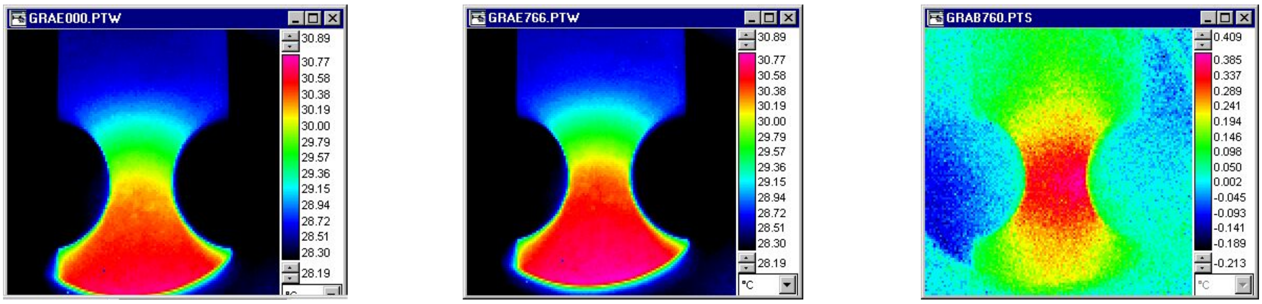
(1b) Granite specimen

Figure 1: Experimental setup of infrared thermography on a granite specimen.

INFRARED THERMOVISION OF ROCK FAILURE

In the laboratory, a fully digital servo-hydraulic test machine, MTS 100 KN, was used for uniaxial loading test. The test machine is controlled by a sophisticated closed-loop electronic control system. The sample is scanned in a non-destructive, non-contact manner by means of an infrared thermographic system. The thermal image is shown on the

monitor screen (Fig. 1). Temperature differences in heat patterns as fine as 0.1°C are discernible instantly and represented by several pseudo color grades.
Brittle geomaterials often present a very low thermomechanical conversion under monotonic loading. In addition the thermal image of the specimen is often affected by several other factors such as the induced heat of the loading machine system, the undesired effects of the specimen ends, etc. This difficulty can be overcome when using thermal image subtraction or *differential thermography*. This procedure of thermal image processing readily evidences the manifestation of damage caused by the loading application between the two thermograms. The resulting image is a subtracted image showing the temperature change between two compared images, obtained under nearly identical test conditions, as shown in Fig. 2. This thermal image processing provides quantitative values of dissipation. The damaged areas are precisely located and highlighted by heat patterns in pseudo colors.

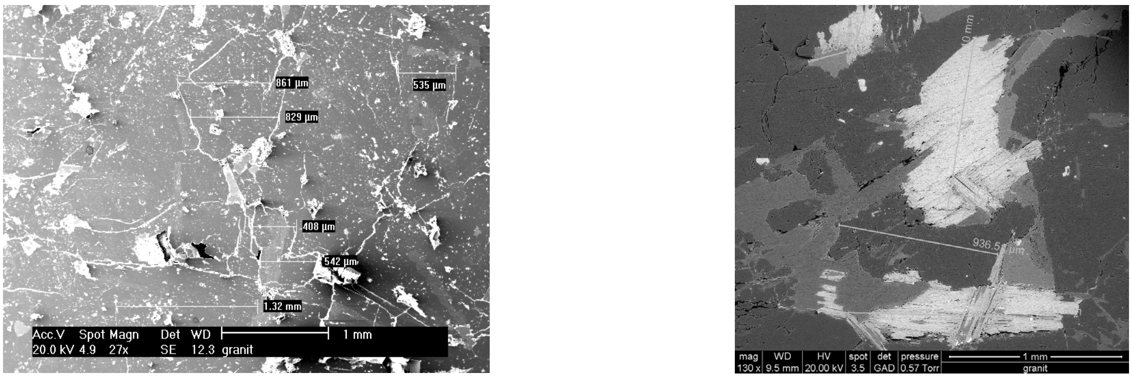


(2a) Thermogram recorded at reference load level. (2b) Thermogram recorded at a given load level. (2c) = Thermogram (2b) – Thermogram (2a).

Figure 2: The differential infrared thermography enhances the localization of intrinsic dissipation (temperature changes are given in °C).

EXPERIMENTAL RESULTS

The proposed technique has been applied in our laboratory on two brittle rock specimens: Massif Central diorite (France) and Viseu granite (Portugal).

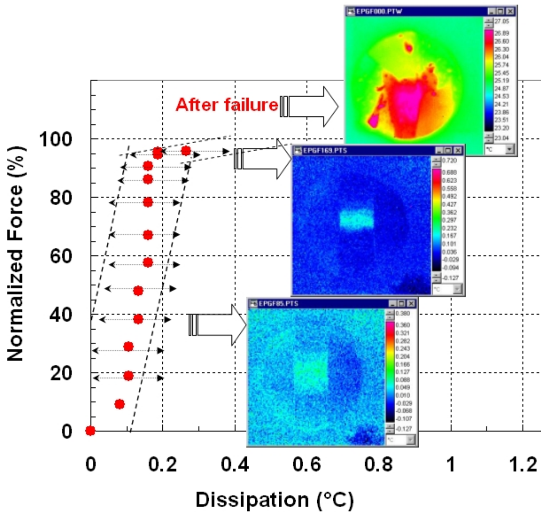


(3a) Quasi homogeneous diorite D. Grain size 400-800 µm, plagioclase feldspar (> 60%) and few percents of hornblende and biotite.

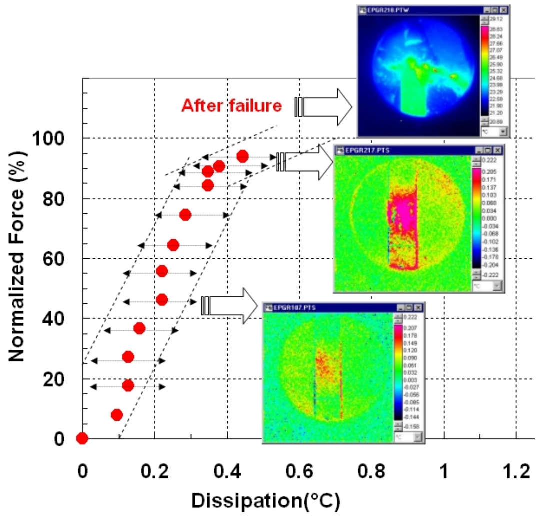
(3b) Heterogeneous granite G. Grain size 100µm-10mm, quartz (≈ 20%), plagioclase feldspar (≈ 20%), orthoclase (≈ 20%), microcline (≈ 10%), biotite and muscovite (≈ 25%), few percents of apatite and altered minerals.

Figure 3: SEM (Scanning Electron Microscopy) images of the 2 specimens

The parameter investigated in this work is the heat generation due to the dissipative behavior of the material under cyclic loading. The thermal images are recorded when the compressive cyclic loading is applied on the test specimen (Fig. 4). The contribution of the plasticity term is revealed by the rapid evolution of dissipation, evidencing the occurrence of damage caused by stress concentration in the central part of the specimen.



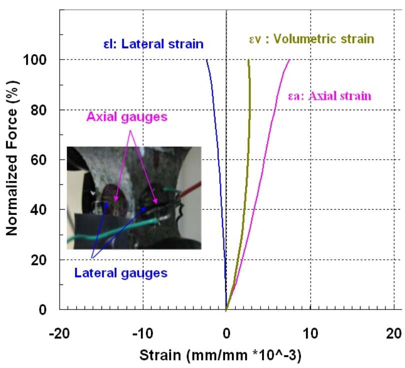
(4a) Quasi homogeneous diorite D.



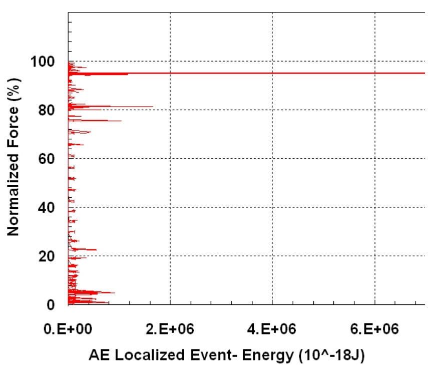
(4b) Heterogeneous granite G.

Figure 4: Different stages of heat dissipation describing the process of the damage extent in the granite specimen (characterized by its compressive strength Rc). Graphical determination of the threshold of acceptable damage TAD of tested materials subject to unconfined loading up to failure.

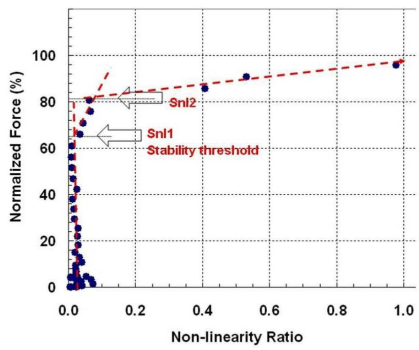
When the compressive loading (maximal cyclic loading at 50Hz and 0.10Rc of amplitude) is applied on the specimen up to failure, the results suggest a threshold of acceptable damage TAD, separating low and high regimes of dissipation or damage. This threshold TAD is readily determined graphically on Figs. (4a) and (4b) for diorite D and granite G owing to the change of slope of the experimental curve. Its value is consistent with characteristic data obtained from other testing techniques based on strain gages, acoustic emission AE or wave propagation phenomena (Fig. 5) despite of their quite different nature.



(5a) Strain based technique



(5b) AE based technique



(5c) Non-linearity based technique

Figure 5: Experimental results obtained when using other testing techniques on granite specimen.

CONCLUDING REMARKS

This work has demonstrated that (1) the evolution of heat change facilitates the detection of damage extent in geomaterials (even for very brittle rocks) subjected to loading up to failure, and (2) the dissipative behavior of geomaterials under solicitations is a highly sensitive and accurate manifestation of damage.
Thanks to the thermomechanical coupling, the proposed differential infrared thermography offers a non-destructive, non-contact and real-time testing technique to observe quantitatively the dissipative mechanism of damage in geomaterials. It thus readily provides a measure of the material damage and allows the definition of a threshold of acceptable damage TAD under load beyond which the material is susceptible to failure.

The main interest of this energy approach is to unify microscopic and macroscopic test data. The parameter intrinsic dissipation under consideration is a scalar quantity, easy to evaluate accurately. Subsequently it may suggest multiaxial design criteria, highly relevant for full-scale testing on engineering rock structures.
In conjunction with others testing techniques based on quite different physical nature, the proposed differential infrared thermography promotes the possibility of investigating more thoroughly the mechanical behavior of brittle geomaterials up to failure from different physical points of view.

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