Journal of Structural Geology 52 (2013) 17–43

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

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

Review article

Time-dependent cracking and brittle creep in crustal rocks: A review

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ARTICLE INFO

Article history:
Received 17 September 2012
Received in revised form
6 February 2013
Accepted 18 March 2013
Available online 11 April 2013

Keywords:
Brittle creep
Stress corrosion
Rock deformation
Experimental
Long-term strength
Static fatigue

ABSTRACT

Rock fracture under upper crustal conditions is driven not only by applied stresses, but also by time-dependent, chemically activated subcritical cracking processes. These subcritical processes are of great importance for the understanding of the mechanical behaviour of rocks over geological timescales. A macroscopic manifestation of time-dependency in the brittle field is the observation that rocks can deform and fail at constant applied stresses, a phenomenon known as brittle creep. Here, we review the available experimental evidence for brittle creep in crustal rocks, and the various models developed to explain the observations. Laboratory experiments have shown that brittle creep occurs in all major rock types, and that creep strain rates are extremely sensitive to the environmental conditions: differential stress, confining pressure, temperature and pore fluid composition. Even small changes in any of these parameters produce order of magnitude changes in creep strain rates (and times-to-failure). Three main classes of brittle creep model have been proposed to explain these observations: phenomenological, statistical, and micromechanical. Statistical and micromechanical models explain qualitatively how the increasing influence of microcrack interactions and/or the increasing accumulated damage produces the observed evolution of macroscopic deformation during brittle creep. However, no current model can predict quantitatively all of the observed features of brittle creep. Experimental data are limited by the timescale over which experiments are realistically feasible. Clearly, an extension of the range of available laboratory data to lower strain rates, and the development of new modelling approaches are needed to further improve our current understanding of time-dependent brittle deformation in rocks.

1. Introduction and theoretical background

Under upper crustal conditions most rocks accommodate deformation in a brittle manner through fracturing and faulting. The general view is that brittle failure is achieved once some critical stress is reached; either the stress needed to generate a new fracture in intact rock, or that required to slide along a pre-existing interface or shear fault (e.g., Paterson and Wong, 2005; Scholz, 2002). Even such frictional sliding along pre-existing faults requires the breakage of asperities at various scales (from the grain-size to crustal-scale fault jogs), and the fracturing of previously-healed fault segments (e.g., Sibson, 1986). The fracture stress of rocks is hence a key parameter controlling the dynamics of the brittle upper crust. Among the many factors affecting the brittle strength of rocks, time (or, equivalently, strain rate) is the least well understood. However, quantifying time-dependent rock deformation is crucial to unravelling the complexities of the evolution and dynamics of the brittle crust. For instance, the presence of cracks allows crustal rocks to store and transport fluids, and even modest changes in crack size, density, or linkage can produce major changes in fluid transport properties. Time-dependent rock deformation therefore has both a scientific and a socio-economic impact since it controls the precursory phase of important geohazards such as earthquake rupture (Main and Meredith, 1991) and volcanic eruptions (Main, 1999; Heap et al., 2011), and also influences effective recovery of hydrocarbon and geothermal energy resources (Cornet et al., 2007), the integrity of underground mines and excavations (Diederichs and Kaiser, 1999) and the long-term storage of hazardous waste (Nara et al., 2010) and CO_2 (Trippetta et al., 2013). Our current lack of understanding in this area has recently been highlighted by UNESCO, and “Understanding Slow Deformation before Dynamic Failure” was one of the two priority areas for study within the Natural Hazards theme of its International Year of Planet Earth (Ventura et al., 2010).

The goal of this review is to summarize our current knowledge of time-dependent fracturing and brittle creep of rocks. A major

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0191-8141/$ – see front matter
http://dx.doi.org/10.1016/j.jsg.2013.03.007

challenge in this field is to understand how, and to what extent, microscopic (grain scale) time-dependent crack growth processes are linked to the observed macroscopic mechanical behaviour of rocks. In order to discuss these issues, in the remainder of the introduction we will recall the key concepts underlying our understanding of brittle fracture, and then introduce the physico-chemical mechanisms responsible for time-dependent crack growth.

1.1. Propagation of single cracks in rocks

Crustal rocks generally contain finite porosity comprising some combination of open pores between grains, triple-junction voids between crystalline phases, grain boundary voids and open microcracks, even at considerable depth (see review by Kranz, 1983). These defects act as stress concentration points from which cracks can nucleate and propagate. Above some threshold density, such cracks will interact and coalesce until eventually macroscopic failure ensues, commonly via the generation of a shear fault. Therefore, in order to understand the micromechanics of brittle failure controlled by crack growth, it is useful to replace the concept of a critical stress controlling brittle strength with the concept of a critical stress concentration controlling crack propagation.

Following the pioneering work of Griffith (1921), Irwin (1958) showed that by measuring the force required to cause unstable propagation of a crack of known length and geometry it was possible to determine the fracture resistance of any material. Lawn (1993) gives a complete analysis of the manner in which the presence of cracks modifies the local stress and displacement fields in a stressed elastic solid, and provides a general expression for the near-field stress distribution of the form:

$$\sigma_{ij} = K \cdot r^{-0.5} \cdot f_{ij}(\theta) \tag{1}$$

where, σ_{ij} is the stress tensor, and r and θ are the radial distance from the crack tip and the angle measured from the crack plane, respectively. The coefficient K is known as the *stress intensity factor*; and describes the magnitude or intensity of the local driving stress close to the crack tip. In laboratory configurations for the experimental determination of fracture parameters, it is usual to simplify the analysis by arranging for uniform loading of a two-dimensional tensile (mode I; Lawn, 1993) crack. Under these conditions, the tensile stress intensity factor K_I is given by:

$$K_I = B\sigma_r\sqrt{\pi l}, \tag{2}$$

where, σ_r is the remotely applied tensile stress and l is the crack half-length. B is a dimensionless parameter that describes the crack and loading geometry, and has been tabulated for a wide range of crack configurations (e.g., Sih, 1973; Tada et al., 1973). Classical linear elastic fracture mechanics predicts that a crack will propagate dynamically at some terminal velocity close to the Rayleigh wave speed once some critical value of K_I, known as the *fracture toughness* (K_{IC}) is exceeded. K_{IC} therefore describes the resistance of the rock to dynamic fracture propagation. At values below the critical value, pre-existing cracks should remain stable and stationary.

This simple, dynamic fracture criterion is, however, generally found to be inadequate to describe fully crack growth in most rocks. A commonly observed characteristic of crustal rocks is that their fracture resistance depends strongly on the environmental conditions under which the deformation takes place, and also upon the rate of deformation. This is especially true at elevated temperature and in the presence of chemically reactive pore fluids. A considerable body of experimental evidence supports the idea that cracks can propagate in a stable, quasi-static manner at values of K_I well below the critical value, K_{IC}, albeit at velocities that are orders of magnitude lower than the terminal velocity associated with catastrophic, dynamic rupture. This phenomenon is known as *subcritical crack growth* and has been reported for a wide range of rock types including sandstones, limestones, granites and basalts amongst others (e.g., see the data compilation of Atkinson and Meredith, 1987a), as well as engineering materials such as glass and ceramics (e.g., Lawn, 1993, Chapter 5). There exists a whole range of micro-mechanisms that could be responsible for subcritical crack growth (reviewed in Atkinson and Meredith, 1987b), including atomic diffusion, dissolution, ion exchange, micro-plasticity and stress corrosion. Nevertheless, the overwhelming body of experimental and observational evidence suggests that growth of pre-existing cracks and flaws by the mechanism of stress corrosion is the dominant mechanism of subcritical crack growth in rocks under conditions prevailing in the upper crust (Anderson and Grew, 1977; Atkinson, 1982, 1984; Atkinson and Meredith, 1987b; Costin, 1987).

Stress corrosion describes the fluid–rock reactions that occur preferentially between a chemically active pore fluid and the strained atomic bonds close to crack tips. For example, in the silica–water system, bridging bonds close to crack tips, that are the main stress-supporting components, are replaced by weaker hydrogen bonds, thus facilitating crack growth at lower levels of stress than would otherwise be the case (Michalske and Freiman, 1982, 1983; Freiman, 1984; Hadizadeh and Law, 1991). To date, the vast majority of experimental data on stress corrosion cracking in rocks has been derived from experiments on single, tensile macro-cracks conducted at ambient pressure. Fig. 1 shows log–log plots of the relationship between crack velocity and the tensile stress intensity factor, K_I, from such experiments conducted on samples of Crab Orchard sandstone (from Atkinson, 1980) and Whin Sill dolerite (from Meredith and Atkinson, 1983) at ambient pressure. Clearly, the level of applied K_I exerts a dramatic influence on the measured crack velocity. A number of theoretical formulations have been proposed to describe this relationship (reviewed in Atkinson and Meredith, 1987b; Costin, 1987), which are of the general form

$$v = v_0 \exp\left(\frac{-H}{RT}\right) f(K_I), \tag{3}$$

where, v_0 is the limiting lower velocity for stress corrosion crack growth, H is the activation enthalpy of the process, R is the universal gas constant and T is the absolute temperature. The function $f(K_I)$ describes the influence of the stress intensity factor on the crack growth rate. Three formulations are commonly used:

$$f(K_I) = \begin{cases} K_I^n, & \text{(4a)} \\ \exp\left(bK_I/RT\right), & \text{(4b)} \\ \exp\left(bK_I^2/RT\right). & \text{(4c)} \end{cases} \tag{4}$$

Expression (4a) corresponds to Charles' law (Charles, 1958), in which n is known as the *stress corrosion index* and is a measure of the susceptibility of the rock to subcritical crack growth in the particular environment of the measurement. Although purely empirical, this formulation has been widely used to describe subcritical crack growth in rocks (Atkinson, 1984). Expressions (4b) and (4c) are exponential forms parameterised by a factor b, and have been derived from reaction rate theory (see for instance Freiman, 1984; Darot and Guéguen, 1986; Wan et al., 1990). In the formulation (4b) (e.g., Freiman, 1984), b is proportional to the crack tip curvature and to the activation volume of the stress corrosion reaction. In the formulation (4c) (e.g., Darot and Guéguen, 1986), b