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Acta Materialia 54 (2006) 3923–3932
Acta MATERIALIA
www.actamat-journals.com

On the role of frictional sliding in the compressive fracture of ice and granite: Terminal vs. post-terminal failure

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Received 1 February 2006; received in revised form 6 April 2006; accepted 8 April 2006
Available online 7 July 2006

Abstract

Biaxial compressive experiments of terminal and post-terminal failure have been performed at −3 and −10 °C on columnar-grained, S2 freshwater ice proportionally loaded across the columns under moderate confinement where Coulombic faulting limits the terminal strength. The results show that the internal friction coefficient that governs terminal failure is closely similar to the coefficient of static friction across the fault. An examination of the literature reveals that granite exhibits the same relationship. When the internal friction coefficients measured here are used to evaluate the recently developed comb-crack mechanism for brittle compressive failure under low confinement, the agreement between theory and experiment is better than first found.

Keywords: Fracture; Friction; Ice; Minerals; Compression

1. Introduction

When rapidly loaded under low confinement, yet within the regime of "static loading", polycrystals of ice and other materials that exhibit brittle behavior reach terminal failure through the initiation, growth and interaction of microcracks. Fundamental to this process is frictional sliding [1–5]. Deformation of this kind occurs across the face of inclined parent cracks, which are closed under the applied pressure, and creates tensile zones. Sliding, we believe, generally occurs non-uniformly, and this leads to tensile zones that are asymmetric with respect to the parent crack [6]. As a result, secondary cracks initiate along one side of the parent, resulting in the formation of comb-like sets [5]. Upon continued sliding, the secondary cracks that constitute the combs lengthen in the direction of the most compressive stress, and then interact to initiate a fault. At this point the overall deformation becomes localized: a narrow band of damage grows rapidly across the load-bearing area, destabilizing the material and resulting in a macroscopic feature inclined typically by about 30° to the direction of shortening [7]. We term this type of feature a Coulombic fault, in recognition of the role of friction in its development. In comparison, another kind of fault, termed a plastic fault, forms when ice [8] and other brittle materials [9] are rapidly deformed under a level of triaxial confinement sufficiently high to suppress frictional sliding. Plastic faults are oriented at about 45° to the axes of maximum and minimum principal stress (i.e., along the planes of maximum applied shear stress) and appear to originate through adiabatic heating [8,9].

In this paper, we focus on Coulombic faulting in ice, particularly on the frictional aspects of the process both before and after terminal failure. The issue is the relationship between the coefficient of internal friction and the coefficient of friction across a Coulombic fault once it has formed. The former coefficient governs terminal failure, while the latter coefficient governs post-terminal failure. From experiment and analysis described below we find that the two coefficients are closely similar, but greater in value than the kinetic coefficient of sliding across smooth

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1359-6454/$30.00
doi:10.1016/j.actamat.2006.04.024

surfaces [10–13]. We find also, from an examination of the literature, that granite exhibits the same relationship. Finally, upon revisiting the comb-crack model [14] of terminal failure and applying the appropriate friction coefficient, we find that this mechanism accounts better than was first apparent for the terminal strength of both ice and granite.

2. Experimental

2.1. The ice

The material we examined was columnar-grained S2 freshwater ice. We grew sheets of the material (~200 mm thickness) from filtered tap water through top-down unidirectional solidification, as described elsewhere [15]. The grain size/column diameter was 4–8 mm, with an average size of ~5 mm. The material possessed a strong growth texture in which the crystallographic *c*-axes of the Ih grains (as determined through thin-section analysis [15]) were randomly oriented in a plane more or less perpendicular to the long axis of the grains; hence the S2 designation [16]. As a result of this texture and of biaxial loading across the columns (more below), inelastic deformation was essentially confined to the plane perpendicular to the long axis of the grains. Terminal failure could then be viewed within the context of two-dimensional deformation.

2.2. Terminal failure

From the parent sheets, we harvested plate-shaped specimens and then milled them to finished dimensions (152 mm × 152 mm × 25 mm parallel to the columns). Following the procedure described earlier [15] (shown schematically in Fig. 1 of Ref. [15]), we loaded the specimens biaxially across the columns to terminal failure, using a calibrated servohydraulic loading system housed within a cold-room. The load was applied between solid brass platens. The minor stress (σ_{22}) was applied in direct proportion to the major stress (σ_{11}) and the loading path was defined by the stress ratio $R = \sigma_{22}/\sigma_{11}$. Displacements were measured using calibrated extensometers, as described earlier [15]. The strain rate applied along the direction of shortening was $4 \times 10^{-3} \pm 2 \times 10^{-3}\ \text{s}^{-1}$, which was sufficiently high to impart brittle behavior over the whole range of confinement $0 \leqslant R < 1$. We performed the experiments at -3 ± 0.3 °C and at -10 ± 0.2 °C, after equilibrating the ice. Results from the strength tests at −10 °C were reported earlier [15], but are included here for reference. As will become apparent, the behavior at the higher temperature replicated the lower-temperature behavior. For that reason, we performed fewer tests at the higher temperature, especially within the high confinement regime where Coulombic faulting does not operate (more below). The terminal failure stress was taken as the highest stress recorded during an experiment, in keeping with earlier practice [15].

2.3. Post-terminal failure: sliding across Coulombic shear faults

We performed post-terminal compression tests at both −3 and −10 °C. First, we introduced a Coulombic fault into test specimens of the kind described above. The only difference was that we increased the specimen thickness to 52 mm to reduce any effect of material loss at the edges of the fault. (The increase in specimen thickness had no significant effect on the terminal failure stress.) To establish a "standard fault" that would serve as a reference for sliding under a variety of conditions, including the ones explored here, we introduced all faults at −10 °C, by loading along the path $R = 0.1 \pm 0.01$ at the same strain rate under which terminal failure was measured. Other than being oriented slightly differently (more below), faults introduced at −3 °C were microstructurally indistinguishable from faults introduced at −10 °C. Occasionally, conjugate faults developed, but more often a single fault ran through the specimen, as shown in Fig. 1. We examined the behavior only of single-faulted specimens. Once the fault was introduced and before the ice was allowed to deform past the point of terminal failure, we unloaded the specimen at the same rate as the load was applied, removed it from the loading system, and then placed it in a cold-room at −10 °C.

Next, we carefully removed sections to the left side and to the right side of the fault, labeled A and B in Fig. 1a (the faulted material possessed enough cohesion to allow machining), and then placed the specimen back in the loading system. At this point we introduced 20 mm thick shims of polished brass (sketched in Fig. 1(b)) to prevent crushing of the apexes during subsequent loading. Also, we placed a thin (0.15 mm) sheet of polyethylene between the ice and all metal interfaces to reduce ice-platen friction. Had we not removed side sections A and B and simply placed the shims over the two sliding plates, but offset from the centerline to avoid crushing of the apexes, a moment would have developed. Upon comparing results obtained using the present procedure with preliminary results [17] obtained without removing the side sections, we found that the moment affects the measurements, leading in the end to significantly lower values of the friction coefficient [18].

Finally, we biaxially reloaded the specimens, again proportionally until sliding was induced in the same sense as when the fault was initiated. During this phase of the experiment, we varied the loading path from test to test up to R_c, where $R_c \sim 0.2$ and ~0.1 at −3 and −10 °C, respectively; for higher confinements, frictional sliding in the X_1X_2 loading plane (Fig. 1) was completely suppressed and failure occurred via out-of-plane spalling in the X_3 direction (more below). Thus over the range of confinement explored, post-terminal failure, like terminal failure, could also be viewed as two-dimensional deformation.

Although we introduced all faults at −10 °C, we performed the sliding experiments at both −3 and −10 °C, as already noted. At the lower temperature, the lapsed time between the introduction and the subsequent sliding across