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Frictionless shear at great depth and other paradoxes of hard rocks

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Abstract

Shearing with very low friction is regarded as responsible for the high-energy release from deep-seated earthquakes and rock bursts in deep underground mines, but in spite of considerable attention to the problem no consensus of opinion has been reached regarding the physical explanation for the low friction. Alternative hypotheses include melting, lubrication, excess pore pressure, velocity effects and vibration at the interface. Here, however, we propose that under high confining stresses, shear fractures developing in pristine hard rocks can exhibit dramatically low shear resistance over a certain displacement range, before the residual frictional strength is mobilized, due to the intrinsic nature of the fault structure. This feature is due to a special fault structure formed during the fault development. The proposed phenomenon can explain a number of anomalies observed in the field and laboratory conditions, but in particular the very high energy released from deep-seated earthquakes and rockbursts.

Keywords: Shear fracture; Low friction; Intense violence; Rockburst; Earthquake

1. Introduction

Observations of unstable fracture processes in hard rock under laboratory conditions [1], in deep mines (from rockbursts) [2], and during deep-seated earthquakes [3–5], show abnormally intense violence, which has been explained by very low friction following fracture. A number of mechanisms have been proposed that might account for such low friction during dynamic shearing, such as local melting within the shear band [3], lubrication [4], trapped high excess pore pressures [5], the effect of shearing at very high strain rates [6], and transverse vibration at the shearing interface [2]. However, there is still no consensus regarding the primary mechanism for the very low friction. Hickman, in his review article [7], summarized the current situation in this sphere of knowledge:

> As this weakness is contrary to traditional views of fault strength based upon laboratory experiments, the Earth science community is left in the awkward position of having no generally accepted paradigm for the mechanical behaviour of faults at depth.

The present paper draws attention to the fact that despite the comprehensive study of the frictional rock behaviour after failure [8–12], the transition mechanism from intact cohesive strength into residual strength during development of the shear fracture has still not been studied comprehensively for pristine hard rocks (e.g. granite, basalt, dolerite, diabase, quartzite, etc) failed under high confining pressures in excess of ~50 MPa. The difficulty is that these rocks respond in such a brittle manner under high confining pressure [1] that even modern stiff and servo-controlled loading systems are unable to control the fracture process. The existing models of shear fracture development [13–18] are based on experimental results obtained at relatively low confining pressures where the behaviour of pristine hard rocks is less brittle [19] or on more ductile rocks [13]. So, the transition mechanism from intact to residual strength is still essentially unexplored under conditions of the extreme brittleness that hard rocks exhibit at high confining pressures.

Here we propose that shear fractures developed in pristine hard rocks under high confining stresses can exhibit dramatically low shear resistance over a certain displacement range, due to the special fault structure. The displacement range over which the friction remains

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very low (theoretically as low as zero) is linked to the width of the shear zone, after which the residual shear strength is mobilized. The proposed phenomenon can explain a number of anomalies observed in the field and laboratory, in particular the very high energy released from deep-seated earthquakes and rockbursts. Increasing brittleness with increasing confining pressure, instead of the expected increase in ductility, which has proved a paradoxical feature of hard rocks [1], follows logically from the fault structure identified. A practical outcome from this work is the improved understanding and quantification of earthquake and rockburst mechanisms that involve shear rupture.

2. Experiments

Experiments were conducted on dolerite specimens obtained from a depth of 712 m using standard rock-coring methods from a seismically active gold mine (Junction Mine) in Australia. The cylindrical specimens were 36 mm in diameter and 72 mm long, and all were monolithic without any visible defects. The grain size ranged from 0.05 to 0.7 mm. Both ends of each specimen were ground to achieve a parallelism of better than 0.02 mm.

A super-stiff servo-controlled triaxial testing machine designed and fabricated at the University of Western Australia was used for the testing programme (for details, see www.cofs.edu.au). The machine involves a monolithic loading frame with stiffness of 20 MN/mm. The calibrated total stiffness of the machine for specimens loaded in the pressure cell is 2.2 MN/mm. The apparatus incorporates a unique wedge mechanism which allows most of the elastic energy accumulated within the hydraulic actuator to be isolated from the sample during the post-peak stage of specimen deformation. This can increase the loading stiffness up to a maximum of 4 MN/mm. The machine loading capacity is 2000 kN and the maximum confining pressure provided by silicone oil is 200 MPa. Servo-control of load, strain and confining pressure is provided.

Each specimen was placed between two steel end-caps and sealed by a rubber sleeve. An axial extensometer and two lateral extensometers (located orthogonally) were fixed to the specimen. The axial transducer was used to control the strain rate between 5 and 10 microstrain/s prior to the peak strength. Signals from one of the lateral transducers most suitably oriented to the developing shear fracture were used to control the test (where possible) in the post-peak region. A low aspect ratio load cell, comprising a solid steel cylinder with diameter of 40 mm and length of 50 mm, was located within the pressure chamber immediately below the specimen lower cap. The output from the load cell was provided by strain gauges glued close to the cylinder axis within special small holes drilled horizontally into the load cell, providing excellent linearity with load.

Two independent acquisition systems were used for recording signals in static and dynamic (unstable failure) regimes. The dynamic system was triggered when spontaneous fracture occurred. The frequency response of the dynamic recording system was steady up to 200 kHz, which was the maximum sampling rate used in the tests.

The specimens were tested at confining pressures σ_3 of 0, 10, 30, 60, 75, 100 and 150 MPa under normal air-conditioned laboratory conditions. Stress–strain curves for all specimens are shown in Fig. 1. The vertical axis here represents differential stress $\Delta\sigma = \sigma_1 - \sigma_3$. As expected, the peak strengths increase with confining stress, following a typical curved strength envelope. Two important features of the post-peak response, typical for hard rocks, were also observed in these tests, namely: (a) the increasing brittleness and (b) the increasing fracture violence, with increase in confining pressure. At $\sigma_3 = 0$ and 10 MPa, the specimens failed with the formation of a number of long tensile cracks as illustrated in Fig. 1. The post-peak response was controlled easily using the stiff testing machine, because that part of the curve has a negative slope, indicating relatively large specific energy consumption during the strength degradation.

The failure mode for the specimens tested at higher confining pressures was different, comprising a single shear plane inclined at an angle α of 25–30° to the specimen axis. The rock behaviour here is characterized by greater brittleness due to significant decrease in the specific energy consumption during strength degradation. The post-peak branch now has a positive slope initially. Despite this fact the loading system managed to maintain post-peak stability in the test at $\sigma_3 = 30$ MPa, responding to changes in one of the lateral extensometers. However, at $\sigma_3 = 60$ and 75 MPa the brittleness became so high that it was possible only to maintain stability near the start of the post-peak response, after which violent failure occurred. At $\sigma_3 = 100$ and 150 MPa the instability started immediately after the peak strength and was extremely violent.

In all tests the variation of the axial specimen resistance (differential stress) with time was registered during the instability by the load cell adjacent to the specimen. An example of the variation of differential stress with time

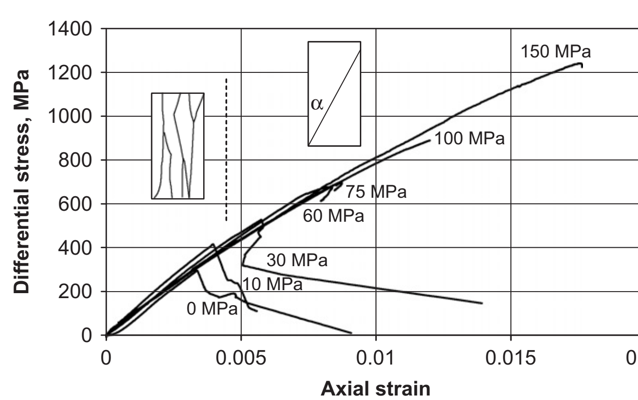

Fig. 1. Stress–strain curves and the fracture mode for dolerite specimens tested at different confining pressures.