Observations of micro-mechanical processes during frictional slip

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Abstract

A procedure has been developed for direct microscopic examination of surfaces during sliding experiments. The observations reveal that frictional state dependence results from an increase of contact area with contact age. Transient changes of sliding resistance correlate with changes of contact area and arise from shifts of contact age during slip.

Introduction

The processes that occur when surfaces are brought into contact are of fundamental interest for understanding a variety of rock properties. Contact processes control the friction and wear of surfaces and control the formation of fault gouge. Rocks and many other materials display a rather complicated, but characteristic, dependence of friction on sliding history. These effects are well-described by empirical rate- and state-dependent constitutive formulations which have been widely utilized for analysis of laboratory experiments slip and for modeling of earthquake processes. Elsewhere in this volume, I summarize some applications of the rate and state formulation to modeling of earthquake clustering phenomena. Although the processes giving rise to state dependency have been the subject of research and inference, the absence of direct observation of surface processes under the conditions that prevail during sliding experiments has hindered definitive understanding of these effects. A procedure has been developed for direct microscopic observation of surface contacts under both stationary and sliding conditions. The observations provide direct data on contact size and stress, and yield insights for the time and displacement evolution of these parameters. Although the results are specifically for bare surfaces, surfaces with gouge layers exhibit similar frictional behaviors and appear to be controlled by similar contact processes.

Method

The method employs roughened surfaces of transparent materials, and experiments have been conducted using quartz, calcite, soda-lime glass and acrylic plastic at normal stresses to 30 MPa (Dieterich and Kilgore, 1994[1]; Dieterich and Kilgore, 1996[2];). When the surfaces are brought together, contact is established only at isolated regions where the stresses are very high. Because the index of refraction of the samples is very different from the air gap between the surfaces, the roughened surfaces scatter transmitted light except where the surfaces are in contact. Hence, when viewed through a microscope, the contacts appear as bright spots against a dark background. To implement this method a conventional servo-controlled testing apparatus has been modified to incorporate beam turners to provide an optical path through the samples to the sliding surfaces. The surfaces are observed using a long working-distance microscope and contact area is measured from digital images of surfaces captured at intervals during an experiment. In addition, the contact images are used to calibrate a continuous measure of contact area obtained from a photocell that records the intensity transmitted across the surfaces. Using digital processing techniques, large numbers of images (over 1000 to date) can be rapidly analyzed.

Results

Static loading experiments yield power law distributions of contact areas over an interval that extends from the smallest contacts that can be resolved (3.5μm^2) to a limiting size that correlates with the roughness of the surfaces [2]. In each material, increasing normal stress results in a roughly linear increase of real area of contact between the surfaces. Mechanisms of area increase are by growth of existing contacts, coalescence of contacts, and appearance of new contacts. Mean contact stresses are consistent with the micro-indentation strength of each material and vary from 400 MPa for acrylic surfaces to • 10,000 MPa for quartz. At these extreme contact stresses, extensive surface damage occurs. However, at the resolution of the optical system, unstable contact failure is not observed [1]. Contact sliding and failure appears to be locally stable processes. Size distributions of the contacts are insensitive to normal stress indicating that the increase of contact area is approximately self-similar.

The contact images and contact distributions have been numerically simulated as contacting surfaces with random fractal topographies [2]. In the model the contact process is represented by the simple expedient of removing material at regions where the surface irregularities overlap. Synthetic contact images created by this simple approach reproduce the geometrical characteristics of the contacts and the observed power law distributions of contact sizes. It is shown that the exponent in the power law distributions depends on the scaling exponent used to generate the surface topography.

Observations of changes of contact area during friction experiments directly correlate with the calculated changes of the state-variable term in the constitutive formulation [1]. Under stationary conditions following slip, the contact area, and the state variable term in the constitutive formulation increase by the logarithm of time. Similarly, during steady state slip, contact area and the state term vary inversely with logarithm of sliding speed. Finally, if sliding speed is changed, both quantities show a displacement-dependent evolution to a new steady-state value over the same characteristic sliding distance, D_C.. These observations provide powerful evidence that the friction state term in the constitutive formulations represents increase of contact area with contact age. Using a single micro-indentor it is found that indentor area also grows by the logarithm of time, and at rates that are comparable to area growth for contacting surfaces. It is concluded that state-dependence of fault strength is a manifestation of the well-known but incompletely understood micro-indentation creep effect.

In numerous previous fault slip experiments the characteristic sliding distance, D_C, for displacement-dependent evolution of state has been found to correlate with surface roughness, and if a gouge layer is present, with gouge particle dimensions and gouge layer thickness. In these experiments it is observed that D_C is proportional to mean contact size. In addition, the shape of the evolution curves can be predicted from the contact size distributions. Together, these results indicate both D_C and the shape of the friction evolution curves can be predicted from surface profiles.

References

[1] Dieterich, J.H., and Kilgore, B.D., 1994, Direct observation of frictional contacts: New insights for sliding memory effects, Pure and Appl. Geophys., **143**, 283-302.

[2] Dieterich J. H. and Kilgore B.D., 1996, Imaging surface contacts: Power law contact distributions and contact stresses in quartz, calcite, glass and acrylic plastic, Tectonophysics, **256**, 219-239..