Earth and Planetary Science Letters 443 (2016) 153–161

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Geometrical evolution of interlocked rough slip surfaces: The role of normal stress

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ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form 6 March 2016
Accepted 12 March 2016
Available online 31 March 2016
Editor: P. Shearer

Keywords:
roughness evolution
fault geometry
direct shear
mechanical work
wear
surface roughness

ABSTRACT

We study the evolution of slip surface topography using direct shear tests of perfectly mating surfaces. The tests are performed under imposed constant normal stress and constant slip rate conditions, to a sliding distance comparable to the roughness scale of the studied surfaces. Prismatic limestone blocks are fractured in tension using four-point bending and the generated surface topographies are measured using a laser profilometer. The initially rough fracture interfaces are tested in direct shear while ensuring a perfectly mating configuration at the beginning of each test. The predetermined sliding distance in all tests is 10 mm and the sliding velocity is 0.05 mm/s. A constant normal stress is maintained throughout the tests using closed loop servo control. The range of normal stresses applied is between 2 MPa and 15 MPa. After shearing, the surface topographies are re-scanned and the geometrical evolution is analyzed. We find that surface roughness increases with increasing normal stress: under normal stresses below 5 MPa the surfaces become smoother compared to the original geometry, whereas under normal stresses between 7.5 MPa and 15 MPa the surfaces clearly become rougher following shear. Statistical spectral analyses of the roughness profiles indicate that roughness increases with length-scale. Power spectral density values parallel to the slip orientation are fitted by power-law with typical power value of 2.6, corresponding to a Hurst exponent of 0.8, assuming self-affine roughness. This power value is consistent for the post-sheared surfaces and is obtained even when the original surface roughness does not follow initially a power-law form. The value of the scaling-law prefactor however increases with increasing normal stress. We find that the deformation associated with shearing initially rough interlocked surfaces extends beyond the immediate tested surface, further into the intact rock material. The intensity of the damage and its spatial distribution clearly increase with increasing normal stress. Wear loss is measured by subtracting the post-shear surface from the pre-shear surface matrices using known reference points. Our measurements indicate that wear loss and roughness evolution are both positively correlated with the mechanical shear work applied during the experiments. We argue, therefore, that normal stress plays a significant role in the evolution of interlocked surfaces, such as geological faults, and strongly affects the energy partitioning during slip.

1. Introduction

Faults in the upper crust are characterized by complex zones of deformed rock that shear during repeated faulting events (Chester and Logan, 1986; Ben-Zion and Sammis, 2003; Wibberley et al., 2008; Faulkner et al., 2010). Most of the displacement along faults is localized at principal slip surfaces exhibiting geometrical irregularity at all measurable scales (Power et al., 1988; Siman-Tov et al., 2013; Candela et al., 2012) and as in other material interfaces the roughness is critical to the understanding of shear and frictional processes (e.g. Bowden and Tabor, 1950; Dieterich and Kilgore, 1994). The presence of gouge and cataclasite zones in natural faults indicates that the fault surface itself evolves through wear production (Power et al., 1988; Wang and Scholz, 1994). In each slip event wear is generated and the initial geometry of the slip surface is continuously modified, a process that has been referred to as "roughness evolution" (Sagy et al., 2007).

Previous roughness evolution studies in the field by means of geometrical measurements of natural fault surfaces suggest that faults smooth with accumulated slip. Wesnousky (1988) observed strike-slip fault traces at geological map scales and discovered that

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http://dx.doi.org/10.1016/j.epsl.2016.03.026

the number of steps along the trace reduces with increased offset on the faults. By comparing profiles along slip surfaces that accommodated dozens to hundreds of meters of displacement to these which sheared less than a meter, Sagy et al. (2007) concluded that roughness parallel to slip orientation reduced due to slip at all measured scales. Brodsky et al. (2011) increased the sampling population and demonstrated that roughness of profiles at lengths of 0.5 to 1 m decreased very gradually as function of the slip amount. Bistacchi et al. (2011) studied paleo-seismic fault surfaces exhumed from seismogenic depths and demonstrated that similar geometrical evolution occurs at these depths.

Surface roughness of fractures was intensively investigated in laboratory experiments as an integral component of contact and shear mechanics (e.g. Bowden and Tabor, 1950; Archard, 1953). Many pioneering works in rock mechanics investigated roughness of faults and fractures in relation to mechanical strength and shear resistance (Patton, 1966; Barton, 1976; Byerlee, 1978). In the last decades, quantitative statistical analysis methods to describe surface geometry were proposed (e.g. Mandelbrot, 1983; Bouchaud et al., 1990; Grasselli et al., 2002) and some were applied to describe rock discontinuities. Amitrano and Schmittbuhl (2002) for example measured the geometry of shear fractures formed by triaxial shear tests and suggested that they exhibited self-affine power-law geometry with Hurst exponents (H) of 0.8 and 0.74 for profiles normal and parallel to the slip direction, respectively. Results obtained with rotary shear tests demonstrated slip rate effects on surface roughness (Fondriest et al., 2013; Boneh et al., 2014; Siman-Tov et al., 2015). These studies focused solely on the roughness characteristics after slip and therefore the actual roughness evolution through shear remained unresolved.

Roughness evolution studies require information about the surface geometry before and after shear displacement. For example, evolution of self-affine geometry, with increasing H as function of the slip amount, was reported for a smooth halite sample that was sheared on a coarse sandpaper substrate (Renard et al., 2012). Davidesko et al. (2014) sheared rough tensile limestone fractures with known initial roughness to increasing slip distances up to 15 mm. They demonstrated that when shearing under relatively low normal stress (2 MPa) surface roughness decreased with increasing displacement, compared to the original roughness.

Normal stress is fundamental in the theory of friction and wear (Bowden and Tabor, 1950; Archard, 1953; Byerlee, 1978) and therefore it is reasonable to assume that it also strongly affects damage and deformation in natural faults which typically yield under tectonic stresses of significant magnitudes. In the present study the effect of normal stress on roughness evolution is examined by means of direct shear experiments coupled with laser profilometer measurements before and after shear. The advantage of the combined mechanical–tribological methodology adopted here is that multi-scale mating surfaces are sheared relative to each other as they do in natural faults, and are mapped with high precision before and after deformation. Moreover, the direct shear system used here allows great control and measuring capabilities during shear displacement. The acquired roughness data is examined both statistically, using spectral analyses, and morphologically, using cross-sections and height maps of the surfaces.

2. Experimental procedure

The experiments consist of several stages: 1) rough tensile surfaces are created using four-point bending; 2) both surfaces are scanned with a laser profilometer; 3) direct shear experiments under constant normal stress to target displacement of 10 mm are performed while ensuring the sheared surfaces are perfectly mating before shearing begins; 4) re-scanning of both surfaces; 5) roughness analysis.

The experimental surfaces are generated from prismatic limestone beams. The starting material is a fine-grained limestone with an average grain diameter of ∼0.4 mm, known locally as “Hebron Marble”. Young’s modulus of 57 GPa, Poisson’s ratio of 0.29 and uniaxial compressive strength of 5.54 and 5.83 were measured for similar samples in a previous work (Davidesko, 2013).

The four-point bending tests utilized the direct shear system with the shear load frame removed and the normal piston used to deliver the axial load (Fig. 1a). A vertical notch, a few centimeters long, was pre-cut to direct the propagation direction of the induced tensile fracture during bending (see Fig. 1a). The produced surfaces were typically 8 cm wide and approximately 11 cm long.

The uniqueness of the surfaces produced this way is that the roughness of one surface matches exactly the roughness of the other, thus enabling the surfaces to slide relative to one another from a completely mating configuration. Furthermore, the roughness of each set (two mating surfaces) is neither predetermined nor reproducible. The experimental fault surfaces in the present study, therefore, differ substantially from the surfaces used in routine friction studies, because they allow examination of multiscale asperity interlocking contacts (Fig. 2).

The experimental fault surfaces are sheared in a hydraulic, servo-controlled, direct shear system (Fig. 1c) to a constant distance of 10 mm at a rate of 0.05 mm/s, under imposed constant normal stress so that the tested interface is allowed to dilate vertically during shear. Normal load is delivered from the axial piston which connects to the top of the shear load frame using a centering pin. The lower shear box rolls on frictionless rollers that are placed between the shear box and the base platen (Fig. 1d).

The fractured interfaces are cast in the shear boxes using concrete in a completely mating configuration so that when initially loaded the interlocking contacts are fully preserved. The shear boxes are placed in the shear load frame which is connected to the horizontal shear piston (Fig. 1c). Six linear variable displacement transducers (LVDTs) are attached to metal plates on both flanks of the steel frames (Fig. 1d); four vertical transducers are used to measure dilation during shear, and two horizontal transducers are used to measure shear displacement. The LVDTs monitor the displacements very close to the sliding interface, thus allowing excellent control capabilities during testing because the shear displacement feedback to the closed-loop system is obtained from the outputs of the two horizontal shear transducers.

The topography of the tested interfaces is obtained by means of laser profilometer (Fig. 1b) and the data are used for roughness analysis. Both top and bottom surfaces are scanned before and after shear. Prior to scanning, the surfaces are cleaned of dust and moisture. Wear particles are removed from the post-shear surfaces using a soft brush and air pressure. The scans are performed parallel to the direction of shear (longitudinal direction of the samples) using a 75 mm lens with a sampling frequency of 10 mm^{-1} and 34.34 mm^{-1} in the longitudinal and transverse directions, respectively. The scans are used to map the entire surface in four parallel strips from which roughness analysis is performed. By comparing the results to higher resolution measurements in the same samples it is concluded that the accuracy of the measurements is robust in our samples for detecting power spectral density values for wavelengths above 0.2 mm. All pre-shear scans had post-shear counterpart scans that covered the same area for later roughness comparison. The acquired scans data are presented using surface matrices of heights.

3. Mechanical results

The mechanical results obtained from six direct shear experiments conducted in the present study and data from one experiment conducted by Davidesko et al. (2014) are presented in