Evolution of slip surfaces geometry and roughness: observations and measurements

Amir Sagy

Geological Survey of Israel

Sagy et al., 2007, *Geology*
Sagy & Brodsky 2009, *Meso-Scale Shear Physics*
Brodsky et al., 2011, *EPSL*
Siman Tov et al., 2013 *Geology*
Davidesko, 2014, *GRL*
Earthquakes are involved with dynamic shear of rock bodies along surfaces.

Shear along surface: Fracture “family” processes (Svetlizky and Fineberg, 2014)
Geometrical evolution of faults: Field observations and laboratory experiments

1. Fracture roughness & Fault roughness measurement

2. Fault surface evolution: Does fault roughness evolve with slip and how?

4. Roughness and wear

5. Roughness evolution: Laboratory observations and first analytical calculation
Fractal lines and surfaces

Real world natural surfaces

Isotopic natural fractal surface
Not all fractures have fractal surfaces
Corrugations and striations parallel to the slip

Anisotropic geometry

Normal Fault: Central Apennines

Strike Slip: Southern Alps
The Leica HDS3000

Field of view is 360° x 270°

Relative positional accuracy: less than 3 mm at 25 m

Spot size: 6 mm at 50 m
What exactly do we scan?

Power spectral density

The strength of the sinusoidal components of the topography over a range of wavelengths using a Fourier decomposition.
Roughness analysis

Self-affine surface

\[ H = K \lambda^\zeta = \sqrt{\frac{K}{\beta-1}} \lambda^{\beta-2} \]

Power et al., 1987, 1988

Parallel to the slip

Normal to the slip
Fault roughness, statistical measurements

1. Faults are rough in all scales
2. Self similar surfaces

\[ H_{\text{RMS}} = C \lambda^\zeta \]
Variation of roughness exponent: First clue for roughness evolution

1. Self affine surfaces

2. Scale dependent roughness parallel to the slip

H ≈ 0.8: Shear fractures

Amitrano and Schmittbuhl (2002)
How fault roughness evolves with slip?

Western US

Roughness measurements of fault Profiles

<table>
<thead>
<tr>
<th>Profile topography</th>
<th>Dixie Valley</th>
<th>Flower Pit 1</th>
<th>Split Mt. 1</th>
<th>Mecca Hills</th>
</tr>
</thead>
<tbody>
<tr>
<td>5mm</td>
<td></td>
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</table>

Profile length: 2mm

Power spectral density (m)

Wavelength (m)

-6
-7
-5
-4
-3
10
0
-1
10
0

Slip Parallel
Fault roughness evolves with slip.

Optimet
Conoscan 2000
Leica HDS 3000

Small slip surfaces
Large slip surfaces
Smooth polished surfaces
How much fault roughness evolves with slip?

\[ H_{L=0.5\,m} = C \cdot \text{Dis}^{-0.1} \]

Roughness evolves gradually with slip.

Brodsky et al., *EPSL*, 2011.
Roughness and wear

Wear: experimental observations

\[ V = V_0 \left[ 1 - \exp \left( - K_1 D \right) \right] + K_2 D \]

Transient wear
Queener (1965)
\[ \frac{dV}{dD} = K_1 (V_0 - V) \]

Steady-State wear
Archard (1956)
\[ \frac{dV}{dD} = \text{Const} \]

Wear of natural faults

Scholz, 1987: linear wear

Power et al., 1988: transient wear

"We suggest that the wear zone thickness for natural faults depends linearly on displacement because the size of the asperities that must be broken increases approximately linearly with displacement. This is a direct result of the approximately self-similar nature of natural fracture and fault surfaces."

Wang and Schoz., 1994
fault surface topography in direct shear experiments

Experimental condition
a. matching surfaces
b. Roughness and displacement: similar scales
c. Normal stress: 2Mpa
d. constant displacement rate of 0.05 mm/s
Roughness evolution with displacement

Before shear

After shear
Roughness evolution with shear displacement
Roughness evolution with normal stress: Nir Badt MSc Thesis

Direct Shear Experiments Results

- Shear Stress, $\tau$ [MPa]
- Shear Displacement, $\Delta u$ [mm]
- Lines represent different normal stress levels:
  - LN1_5 MPa
  - LN10_7.5 MPa
  - LN6_10 MPa
  - LN11_12.5 MPa
  - LN5_15 MPa
  - LN7_15 MPa

The graph shows the evolution of shear stress with shear displacement for different normal stress levels.
Power spectral density and normal stress

Before shear

After shear

<table>
<thead>
<tr>
<th>σ_n (MPa)</th>
<th>PSD (mm³)</th>
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<tbody>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td></td>
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<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>12.5</td>
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<tr>
<td>15</td>
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</tbody>
</table>

Wavelength (mm)
Surface geometrical evolution: 5Mpa

LN1, load=5 MPa

Before shear

After shear
Surface geometrical evolution: 5Mpa
LN10-T Δ=Pre-Post

LN10 – 7.5 MPa

Profile no.250

Profile no.400
Surface geometrical evolution
LN11 – 12.5 MPa (Bottom)

Post Shear

Three main zones
a. parts of the original surface.
b. Striated area
c. Penetrative damage area

striations

Penetrative damage
Preliminary results

Variations of $\mu$ with Normal Stress for Rough Self-Similar Surfaces

Friction Coefficient, $\mu$

Normal Stress, $\sigma_n$ [MPa]
Variations of the Shear Stress Drop with Roughness Evolution

Peak Shear Stress vs PSD ratio
Striations and bumps (damage zone)

Strike Slip: Southern Alps (Italy) few m of slip

Flowers Pit, Oregon
Stresses and yielding along a wavy fault

Following Chester & Chester, 2000

Orientation and values of $\sigma_1$ along wavy fault

Stresses (Pa)

Normalized location (Z/L)

Normalized location (L)

Orientation and values of $\sigma_1$ along wavy fault

Stresses (Pa)

Location along the fault (X/L)

Location normal to the fault (Y/L)

Location along the fault (X/L)

Location normal to the fault (Y/L)
Slip on pre-exist rough surface before yield of the host rock

Predictions
1. Magnification and rotation of the stress field near the fault surface (Chester and Chester, 2000)
2. Slip along preexisting surface with a realistic geometry requires internal yielding of the host rock.
3. Larger amount of slip before internal yielding is predicted for smoother surfaces.
Some main results

1. Fault surface evolves with slip by:
   a. decreasing of the roughness exponent $\zeta_i > \zeta_f$
   b. decreasing of asperities $C_r > C_i$

   It is not clear (at least for me) if they remind fractal along the entire evolution process

2. Fault roughness evolve gradually with slip: $H \approx 2 \times 10^{-3} D^{-0.1}$

3. Experimental results a: Wear smooth the roughness at all measurable scales

4. Experimental results b: normal stress increases the damage. Lenses of intense damage zones are generated and might explain the existence of large scale bumps on fault surfaces

5. Damage is scales with the shear stress drops
Branches and splays: of fault deformation

Transient wear?
Fault displacement (m)
Thickness of the cohesive layer (mm)
Thickness of the wear layer as function of slip
Wear

RMS = RMS_{OR}

RMS > RMS_{OR}

RMS < RMS_{OR}

RMS(L) = RMS_{OR}, RMS(L) > RMS_{OR}, L > L