Simulating Melting of Fault Gouge at the Local Scale

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I – Introduction

II – Simulations

III – Influence of Fault Thickness

IV – Molten Gouge

V – Influence of Melt Proportion

VI – Perspectives
Motivation of the study:
- Saw-cut triaxial experiments on Westerley granite under $\sigma_3=45\text{-}180\text{MPa}$ (Aubry 2020)
- Temperature trackers (amorphous carbon layer) showed clear evidences of flash heating

Aubry et al. (2019), GRL, 45(22)

I - Introduction
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- SEM–TEM observation showed partial or total melting of the gouge layer

Cross section of amorphous melt layer with micro/nanometric gouge particles

Initial gouge particles
Size ~ 1µm

Completely established layer of melt
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How does this layer appear, and what are its implications on friction? Can we model this?
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Discrete Element Modelling (DEM, Newtonian dynamics) simulation protocol:

- We assume a perfectly established comminuted gouge with \( \sim 1\mu m \) angular grains.
- Sample width of 100\( \mu m \), thickness can vary.
- Normal stress \( \sigma_n = 200 \text{ Mpa} \), sliding velocity \( V = 10 \text{ m/s} \), periodic lateral boundaries.
- Code MELODY2D; plane strain; Simulated time: 20-50 \( \mu s \); time step \( \sim 1\text{ps} \).

\[\text{Mollon (2018), Comp. Part. Mech, 5}\]
Local contact conditions:

- Contour of the particles described by a piecewise linear function. Two-pass node-to-segment algorithm.
- Angular shapes and penalized frictional contact between gouge particles, $\mu=0.8$ (calibrated in Mollon et al. 2020).

*Mollon et al. (2020), Granular Matter, accepted*
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- Any mechanical energy dissipated by intergranular friction is converted in heat and shared between the contacting grains.

- Temperature of each grain increases. No heat diffusion by contacts (yet).

*Mollon et al. (2020), Granular Matter, accepted*
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We first vary the thickness of the gouge layer, from ~9µm to ~90µm.

- Shear distributed in the whole thickness for 9µm, 22µm, and 45µm, but localized for 90µm.
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- Shear distributed in the whole thickness for 9µm, 22µm, and 45µm, but localizes for 90µm.
- Confirmed by final distribution of the Volume Fraction of the granular packing
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- Shear-rate is thus very high for small layer thickness, but stabilizes above a thickness of 45µm
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- Shear-rate is thus very high for small layer thickness, but stabilizes above a thickness of \( 45\mu m \).
- Temperature increase of the grains follows the same logic.
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- Shear-rate is thus very high for small layer thickness, but stabilizes above a thickness of 45µm
- Temperature increase of the grains follows the same logic
- Temperature maps show a linear increase with time, with a maximum value at the center of the sheared layer
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Statistics on the temperature increase for each grain

- We focus on the ~45µm-thick sample
- Divided in 5µm horizontal layers for sub-sampling

Temperature increase in each grain as a function of its position in the sheared layer:
Statistics on the temperature increase for each grain

- We focus on the ~45µm-thick sample.
- Divided in 5µm horizontal layers for sub-sampling.
- If temperature of each grain is normalized by the average temperature in its horizontal layer, probability distributions of grains temperature elevations collapse to a lognormal distribution.
Melt layer:

- Temperature statistics indicate that most of the melt will initially form in a ~10µm thick central layer.
- Good agreement with experimental observations (8-16µm melt layer).
Simulation of a fully molten central layer

- Proxy for the melt rheology: highly deformable, incompressible, viscoelastic grains (Mollon 2018)

- Deformability simulated by a multibody meshfree method (DEM enriched with continuum mechanics), in the code MELODY2D

Mollon (2018), Granular Matter, 20(39)
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- Deformability simulated by a multibody meshfree method (DEM enriched with continuum mechanics), in the code MELODY2D

- No friction and no cohesion at contacts, but energy dissipation by internal viscosity and subsequent heat creation.

- Still no heat diffusion through contacts

- Equivalent viscosity: ~12.1 Pa.s (in the low range for molten silicates, Wallace et al. 2019)

Mollon (2018), Granular Matter, 20(39); Wallace et al. (2019), Geoc. and Cosmo. Acta 255

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Simulations Results

<table>
<thead>
<tr>
<th>X-displacement (μm)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>200</td>
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- **Only solid grains:** $\mu = 0.48$
- **Fully molten central layer:** $\mu = 0.08$

- Distributed shear in the whole granular layer
- Localized accommodation in the central melt layer, solid grains unaffected
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Low and heterogeneous connectivity

Large and homogeneous connectivity, especially in the melt layer

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- Large and homogeneous connectivity, especially in the melt layer
- Important dilatancy
- No volume change in solid grains, Volume Fraction close to 1 in the melt layer
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<td>Distributed and important temperature elevation</td>
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<td>Only moderate temperature elevation in the melt layer</td>
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Investigation of the progressive creation of the melt layer:

9 simulations with increasing proportions of melt $\Phi_M$ in the central layer (5% to 100%, partial views)
Large influence of $\Phi_M$ on the flow regime:

-A larger proportion of melt in the central layer promotes localization and increases local shear rate.

-With increasing $\Phi_M$, temperature elevation first increases in the central layer (due to localization) and then decreases (fluidization of the central layer).

**Graphs**

- **Progressive localization**
  - $\Phi_M = 0\text{-}40\%$: Increase of temperature elevation.
  - $\Phi_M > 50\%$: Decrease of temperature elevation.
Large influence of $\Phi_M$ on the flow regime:

- A larger $\Phi_M$ also increases the connectivity of the grains, especially in the central layer.
- It also increases the density of the granular packing, especially in the central layer.
Friction and energetic budget

- Friction coefficient of the interface decreases non-linearly with $\Phi_M$
- Based on the type of energy dissipation (solid or deformable grains), friction is decomposed into two contributions: a Coulomb term and a viscous term.
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- Friction coefficient of the interface decreases non-linearly with $\Phi_M$
- Based on the type of energy dissipation (solid or deformable grains), friction is decomposed into two contributions: a Coulomb term and a viscous term.
- These contributions do not evolve linearly with $\Phi_M$
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Future work will consist in writing a friction law for melting-related dynamic weakening:

- Adding the contributions of:
  - a Coulomb term (related to normal stress and granular properties of the gouge)...
  - a Viscous term (related to sliding velocity, layer thickness and melt viscosity)....
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... both of them being functions of the melt proportion...
... which is a function of temperature elevation and shear localization!
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  ... which is a function of temperature elevation and shear localization!

- Formulation of the weakening law in terms of sliding distance.
- Dialog and comparison with existing models, e.g. flash weakening.
- Introduction of heat diffusion in the surrounding medium.
Thank you

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