Friction is fracture: Slippery surfaces and frustrated cracks

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1480 - Da Vinci

1699 - Amontons

1785 - Coulomb

\[ F = \mu N \]

F is independent of the area of contact

\[ \mu_{\text{static}} \neq \mu_{\text{dynamic}} \]
Small scales: technological challenges

- Reducing friction (MEMS).
- Reducing wearing of surfaces.
- Improving lubricants efficiency and durability.
- Biomimetic approach.

Large scales: geophysical challenges

- Earthquakes and landslide mechanisms.
- Predictability.
- Effect of heterogeneities of interfaces (water, melted rocks, roughness).

What we usually know about friction

*Da Vinci, Amontons, Coulomb*

$$F_S < \mu_s F_N \Rightarrow \text{no motion}$$

$$F_S = \mu_s F_N \Rightarrow \text{motion}$$

What actually happens at the interface

- **Net contact area** = \( A \ll \text{Nominal contact area} \)
- **Huge pressures** deform the contacts
- **Pressure** = yield stress, \( \sigma_Y \Rightarrow A = \frac{F_N}{\sigma_Y} \)
  - \( A \) is proportional to the normal load

**EARTHQUAKE!**

The onset of friction ⇔ fracture of the discrete contacts that form the interface

*F.P. Bowden and D. Tabor (1950)*
*S. M. Rubinstein et al (2004)*
Interface slip is mediated by crack-like rupture fronts

Fronts have been observed experimentally in many different systems:

- **PMMA**: Rubinstein et al. (2004)
- **Homalite**: Xia et al. (2004)
- **Granite**: Passelègue et al. (2013)
- **Gels**: Baumberger et al. (2002), Latour (2011)
- **PDMS**: Chateauminois et al. (2008), Prévost et al. (2013)

We’ll show that: The **stresses** driving these fronts are described by **Fracture Mechanics**
Outlines

1. The experiment


3. Arrested ruptures: Predictability of “laboratory earthquakes”

4. Lubricated interfaces: Slippery can be tough
Experimental setup

Real contact area measurement

Fast Camera
580,000 fps

2D-strain tensor measurement at 1 MSamples/s

\( F_N \)
\( F_S \)

\( I_{\text{Transmission}} \propto A \)

\( I_{\text{Incident}} \)
\( I_{\text{Reflected}} \)

PMMA


Svetlizky and Fineberg (2014)
A typical experiment

\[ F_N \sim 300-700 \text{ kg} \]
\[ F_S \sim 100-500 \text{ kg} \]

\[ \frac{m}{A} = \frac{F_S}{F_N} \]

\[ x (\text{mm}) \]
\[ \text{time (s)} \]

\[ A/A_0 \]

\[ \text{time (s)} \]
\[ x (\text{mm}) \]
Rupture Fronts

At long (~ sec) time scales:

Each line = snapshot of the real area of contact along the entire interface
1.5\(\mu\)sec between lines

Block detachment is mediated by propagating crack-like fronts

C\(_R\): Rayleigh wave speed (1255m/s for PMMA)
Fracture Mechanics
Linear Elastic Fracture Mechanics (LEFM)

- Linear elasticity \( \rightarrow \) singular stress at a crack’s tip
- Energy balance \( \rightarrow \) Dissipation = Energy flux into the crack tip
- Speed limit: \( C_R \), Rayleigh wave speed (1255m/s for PMMA)
Fracture mechanics solution (LEFM):

\[ \Delta \epsilon_{ij} = K r_1^2 f(\theta, v) \]

\[ G = \Gamma \]

\[ \Gamma \sim 1 \text{ J/m}^2 \]

Propagation condition \( G = \Gamma \)

Detachment fronts are shear cracks

Strain field measurements \( \leftrightarrow \Gamma \)

Real area of contact - PMMA

Under our conditions: $A \sim 0.005 A_0$

$A/A_{(t=0)} \sim 20\%$

$C_f$

$x-x_{tip}(\text{mm})$

$\Gamma_{bulk} = \Gamma \cdot A_0/\Delta A = 1 / (0.2 \times 0.005) \sim 1000 \text{ J/m}^2$

$\Rightarrow \Gamma_{bulk} \sim \text{the measured bulk fracture energy for PMMA!}$

$\Rightarrow \Gamma$ is proportional to $A$

$\Rightarrow A$ is proportional to $\sigma_{yy}$

$\Rightarrow \Gamma$ is proportional to $\sigma_{yy}$?

$\Gamma (\text{J.m}^2)$

$\sigma_{yy} (\text{MPa})$
Friction rupture fronts are essentially shear cracks (at least when they are moving)

We will now use this to describe related phenomena/questions

1. Arrested rupture fronts
   How far will an earthquake extend ⇔ when will a rupture stop?

2. Lubrication of the interface
   Is friction still fracture?
   Effect of lubricants on rupture onset/dissipation...
ARRESTED RUPTURE FRONTS

Transition from stick to slip is mediated by a rupture front.

Partial ruptures occur before the transition: no macroscopic sliding.

What controls the arrest of the rupture?
Arrested ruptures can result from inhomogeneous stress distributions

Several observations of these partial ruptures: Rubinstein 2007, Maegawa 2010, Katano 2014

Numerical studies of the existence of such ruptures:

Recent study proposed a CRACK ARREST CRITERION

Our work: Experimental verification of the validity of a crack arrest criterion
How can fracture mechanics help?

We have seen that stresses are singular at the crack tip

$$\Delta \sigma_{ij} = \frac{K}{r^{1/2}} f(\theta, \nu)$$

Propagation criterion:
Energy flux = Fracture energy

$$G \sim \frac{K^2}{E} = \Gamma$$

At the arrest:

$$G(v, l) \xrightarrow{v \to 0} G_{stat}(l) = \frac{K_{stat}(l)^2}{E}$$

**Arrest criterion:**

$$G_{stat} < \Gamma \Rightarrow K_{stat} < K_c = \sqrt{\Gamma E}$$

Griffith criterion

Griffith (1920)
Freund (1990)
Arrest criterion:

\[ K_{\text{stat}} < K_c = \sqrt{\frac{\Gamma}{E}} \]

- Determination of \( K_c \) ➔ We know how to determine \( \Gamma \)
- Calculation of \( K_{\text{stat}} \)

\( \Delta \sigma(x) = \) stored stress ahead of the crack

\( l = \text{prospective (predicted) crack length} \)

Fracture Mechanics: \( K_{\text{stat}} \) is determined by the stress drop \( \Delta \sigma(x) \) for all \( x < l \)

\[
K_{\text{stat}}(l) = \sqrt{\frac{2}{\pi}} \int_{0}^{l} \frac{\Delta \sigma(x)}{\sqrt{l - x}} \, dx
\]
Can we **predict crack arrest?**

\[ K_{\text{stat}}(l) = \frac{2}{\pi} \int_0^l \Delta \sigma(x) \sqrt{l-x} \, dx \]

\[ K_c = \sqrt{\Gamma E} \]

![Graphs and data](image)
We have predicted crack arrest once ... is it general?

Bayart et al (2016)
We have shown that is deterministic.

The location of a rupture arrest can be simply defined with a crack arrest criterion.

**WHY ARE WE INTERESTED IN ARRESTED RUPTURES?**

- Confirmation of the fracture-paradigm for understanding friction.
  
  Friction coefficient = force balance
  Fracture mechanics = energy balance

- Prediction of earthquake’s size
  
  An earthquake is a finite size rupture in an infinite size system
LUBRICATED FRICTION

What about lubricated interfaces?

**Coated lubricated interfaces** = Interfaces coated with a film of lubricant

<table>
<thead>
<tr>
<th>LUBRICANT</th>
<th>KINEMATIC VISCOSITY (cSt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicone oil</td>
<td>5</td>
</tr>
<tr>
<td>Silicone oil</td>
<td>100</td>
</tr>
<tr>
<td>Silicone oil</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Hydrocarbon oil (TKO-77)</td>
<td>200</td>
</tr>
</tbody>
</table>
For slippery interfaces, we observe **STICK-SLIP**

and propagating **RUPTURE FRONTS**!
It is more slippery ...

- Coated with a thin layer of oil
- Fully lubricated

Graph showing the ratio $F_s/F_N$ against time $t (s)$.
... BUT

\[ \Delta \varepsilon_{xx} \]

\[ \Delta \varepsilon_{yy} \]

\[ \Delta \varepsilon_{xy} \]

**DRY FRICTION**

**LUBRICATED FRICTION**

\[ \Gamma_{lubricated} = 23 \text{ J/m}^2 \gg \Gamma_{dry} = 2.6 \text{ J/m}^2 !! \]
Fracture energy vs normal stress

- $\Gamma$ is always proportional to normal stress
- Different lubricants have different influence on $\Gamma$
- Viscosity does not affect $\Gamma$...
Coated lubrication

A **WEAKER** interface – smaller friction coefficient

A **STRONGER** interface – higher fracture energy

\[ \Gamma_{\text{lub}} \sim 23 \text{ J/m}^2 \gg \Gamma_{\text{dry}} \sim 3 \text{ J/m}^2 \]
How to explain a high fracture energy $\Gamma$?

LEFM: intermediate scale
Small scale: dissipative zone

Frictional crack – Linear slip-weakening model

*Palmer and Rice 1973*

\[ \Gamma = \frac{1}{2} (\sigma_{xy}^{\text{peak}} - \sigma_{xy}^{\text{res}}) d_c \]

d$_c$ : slip distance over which stresses are reduced (asperity size)

Increase of $\Gamma$: 
- increase of $\sigma_{xy}^{\text{peak}}$ → not measured
- increase of $d_c$ → not measured
- decrease of $\sigma_{xy}^{\text{res}}$ → measured
Linear slip-weakening model relates $\sigma_{xy}^{peak}$ to the dissipative zone size $X_c$:

$$\sigma_{xy}^{peak} = \sigma_{xy}^{res} + \frac{9\pi \Gamma E}{32 (1 - \nu^2) X_c}$$

$X_c$ is the distance behind the crack tip over which contact are broken.

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**Increase of $\Gamma$:**

- increase of $\sigma_{xy}^{peak}$ → YES
- increase of $d_c$ → YES
- decrease of $\sigma_{xy}^{res}$ → YES
Coated lubrication: *Some questions...*

**Peak stress is not** reduced, even increased:

Possibly: Huge pressures at the contacts cause...

*Layering transition* of the highly compressed liquid (e.g. *layering* -Israelachvili, Klein, Granick...) ?

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**Residual strength** is significantly lower.

Possibly: Once motion initiates...

*Lubrication of contacts? ➔* Lubricant recovers a liquid behavior

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Solidification followed by melting could be the answer


NO PARADOX between a low static friction coefficient and a high fracture energy

friction coefficient = nucleation process
fracture energy = interface property, related to propagation

Questions do remain:

Why doesn’t fluid viscosity matter?

Why does lubricant composition matter so much?

High fracture energy = high dissipation ➔ high wear of lubricated machine parts at the onset of motion
SUMMARY

At the onset of motion, RUPTURE FRONTS propagate along the frictional interface. They are ruled by FRACTURE MECHANICS while propagating and at the ARREST.

Along a LUBRICATED interface, fracture mechanics provide a way to observe the complex dynamics of the lubricant layer.

NOT A CLOSED PROBLEM

Nucleation = crack initiation? probably not

What about more complex interfaces? non-cohesive interfaces, textured

What about sliding?
APPLICATION

Can be a rupture arrested by a local increase of the fracture energy?
• $0 < x < 75\text{mm}$: non-lubricated surface

• $75\text{mm} < x < 150\text{mm}$: surfaces coated with hydrocarbon oil (TKO-77).

• $\langle \sigma_{yy} \rangle = 4\text{MPa}$

What will happen to the propagating rupture while entering in the lubricated part?
\[ \Gamma_{\text{TKO-77}} (\langle \sigma_{yy} \rangle = 4 \text{MPa}) = 10 \text{ J/m}^2 \]

\[ \Gamma_{\text{DRY}} (\langle \sigma_{yy} \rangle = 4 \text{MPa}) = 1 \text{ J/m}^2 \]
THANK YOU
\[ \mu = \frac{F_S}{F_N} \]

- Silicone oil 5 cSt
- Silicone oil 100 cSt
- Silicone oil 10^5 cSt
Summary

- **Rupture fronts** mediating the onset of sliding are **shear cracks**
- **Spontaneously arrested ruptures**: arrest location is defined by a **crack arrest criterion**
- **Lubricated interfaces**: the interface **fracture energy** is increased.

**Can we use it?**

- Could we deduce $\Gamma$ along a fault by recording the **displacement field** during a rupture propagation?
  
  *Comparison of the measured value with the estimation by the drop of stress and the event size?*

- Rupture arrest: knowing the **averaged drop of stress for small earthquakes** along a fault, could this criterion used to evaluate **local $\Gamma$** along a fault?

- Increased of $\Gamma$ by lubrication: increase of the **wear of the material**?
Coated lubrication

**Why a Stronger** interface?

List of propositions including ideas of GRC participants:

- **Layering transition** of the highly compressed liquid (*e.g. layering* -Israelachvili, Klein, Granick...)

- **Piezoviscosity** (increase of the viscosity with the pressure and shear rate)

- **Suction** of the liquid at the onset of motion (negative pressure due to capillary bridges)

- **Effect of the pore pressure** on the residual stress

- **Viscous dissipation** in the cohesive zone
\[ \Gamma_{\text{interface}} = \frac{\text{real area of contact}}{\text{apparent area of contact}} \times \frac{\text{number of broken contacts}}{\text{total number of contacts}} \times \Gamma_{\text{bulk}} \]

**NO PARADOX** between a **low static friction coefficient** and a **high fracture energy**

**friction coefficient** = nucleation process

**fracture energy** = interface property, related to propagation

- **Dry interface**
- Silicone oil 5 cSt
- Silicone oil 100 cSt
- Silicone oil 10^5 cSt
- Hydrocarbon oil TKO-77
What we usually know about friction

$F_S < \mu_s F_N \Rightarrow$ no motion

$F_S = \mu_s F_N \Rightarrow$ motion

What actually happens here

The onset of friction $\Leftrightarrow$ fracture of the discrete contacts that form the interface

About the area of contact

Net contact area = $A \ll$ Nominal contact area

Huge pressures at the contact points deform the contacts

Pressure = yield stress, $\sigma_Y$ \quad $A = \frac{F_N}{\sigma_Y}$

$A$ is proportional to the normal load

F. Philip Bowden and David Tabor (1950)
Rupture propagation

Fracture mechanics solution (LEFM):
\[ \Delta \varepsilon_{ij} = \frac{K}{r^{1/2}} f(\theta, v) \]

\( K \leftrightarrow \text{energy flux} \ G \)

Propagation condition \( G = \Gamma \)
\( \Gamma \approx 1 \text{ J/m}^2 \)

Detachment fronts are shear cracks
Strain field measurements \( \leftrightarrow \Gamma \)

Coated lubrication: *Why a Stronger* interface?

An interpretation of the role of the lubricant:

On a coated surface: $\sigma_{lubricated}^{\text{residual}}$ is lower resulting in longer slip, $\delta$

\[
\begin{align*}
\sigma_{xy}^{\text{peak}} & \leq \sigma_{dry}^{\text{peak}} \\
\sigma_{lubricated}^{\text{residual}} & \ll \sigma_{dry}^{\text{residual}} \\
\Rightarrow \Gamma_{lubricated} & \sim \Delta\sigma \cdot \delta \gg \Gamma_{dry}
\end{align*}
\]
Large improvements this last two decades

Development of AFM and SFA: measurements for one single contact
(*Israelachvili, Klein,...*)

Biomimetic approach for both dry and lubricated friction

Development of high-sensitivity seismic captors allowing detection of a large range of types of events (silent to supershear earthquakes)