THE INTERPLAY OF INSTABILITIES IN DRYING COLLOIDAL FILMS

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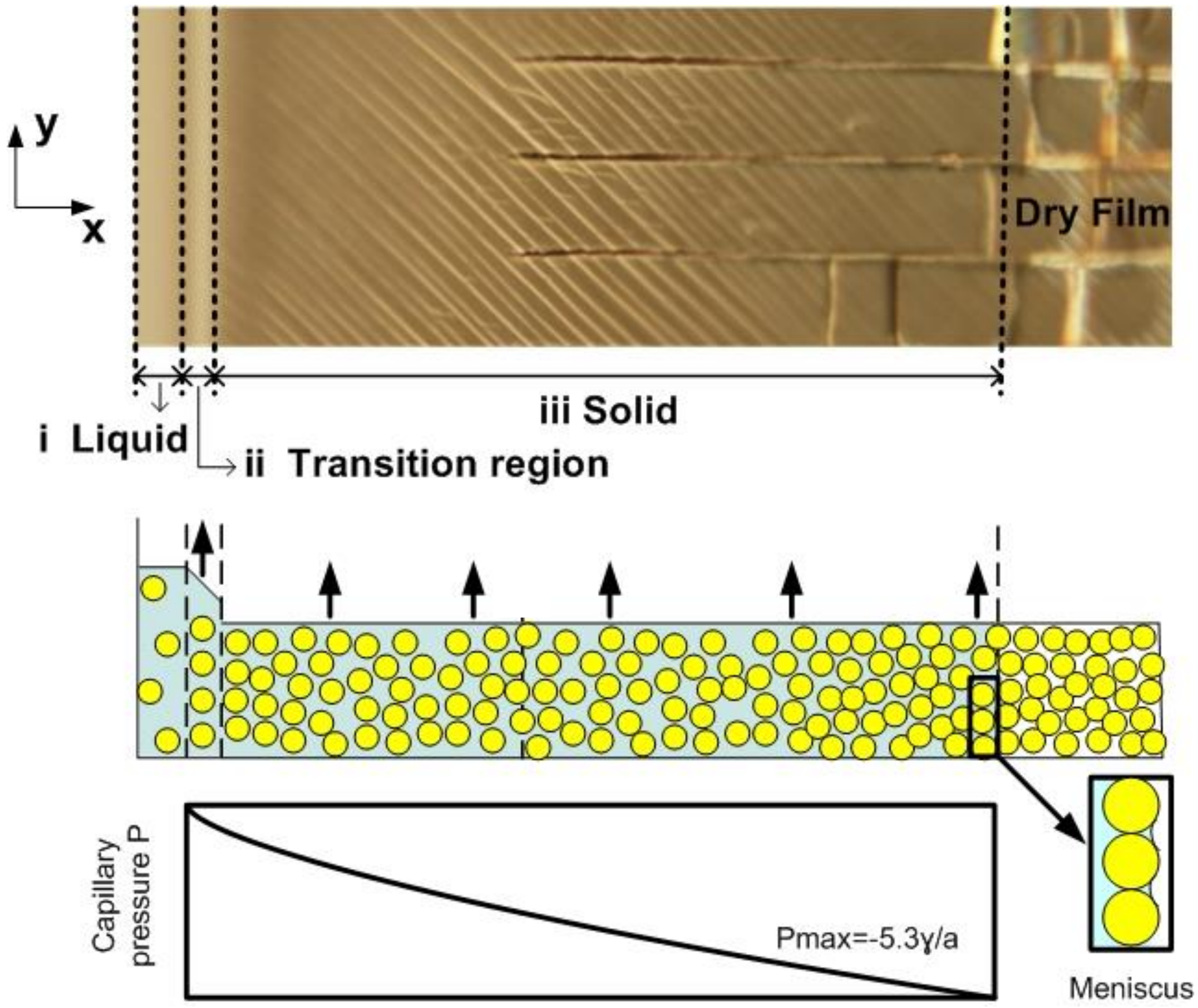
Talk outline

- Introduction
- The role of compaction in Shear Banding
- Delamination induced spalling
- Conclusions

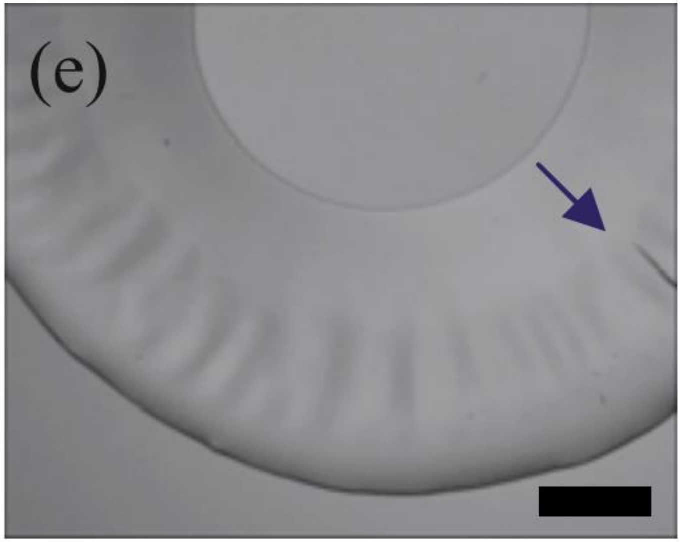
Planar drying of colloidal films



Strain release mechanisms in film formation

Crack formation

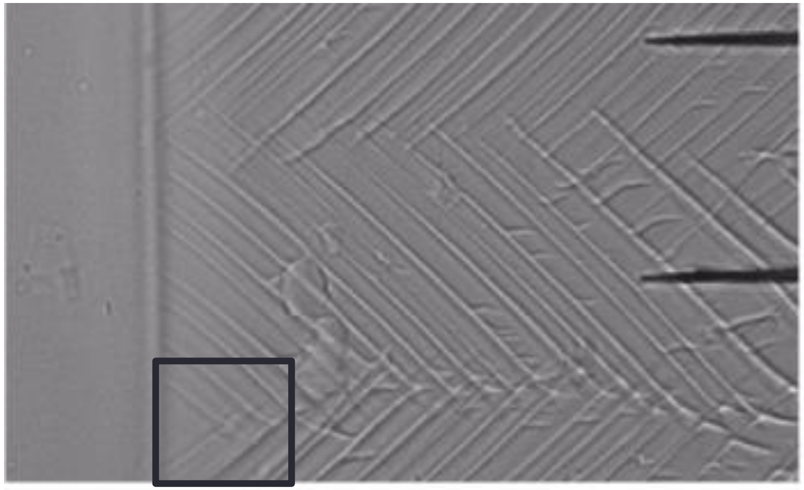
Film Delamination



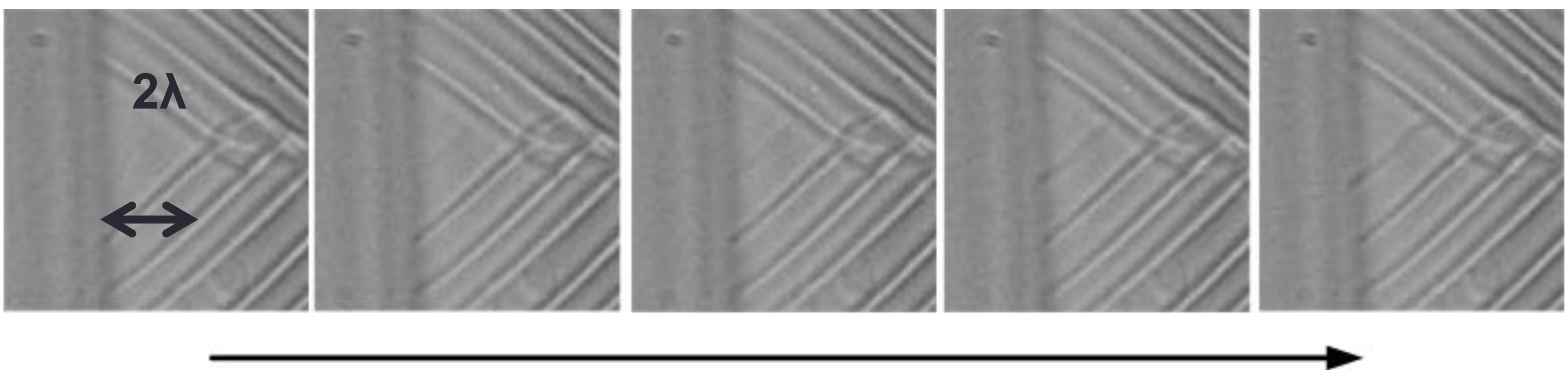
Surface Wrinkling / Buckling

Shear Banding

Shear banding

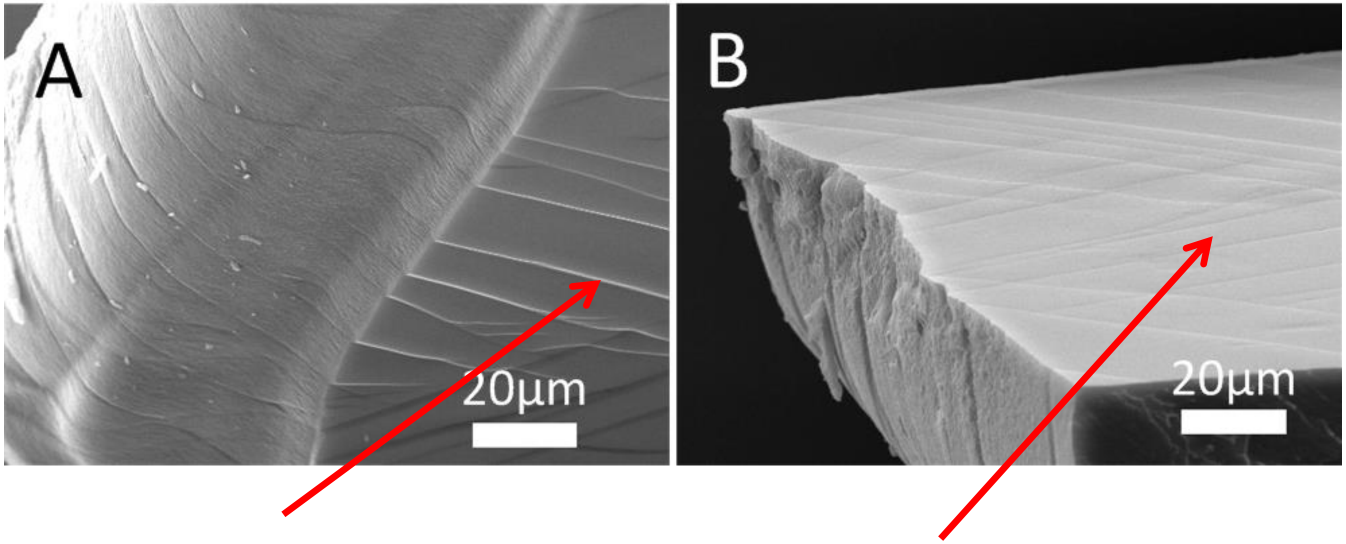


- ❑ **Bands form behind transition region**
- ❑ **Bands form for 50 & 100nm particles but not 200nm and greater.**



0s **0.17s**

Shear banding



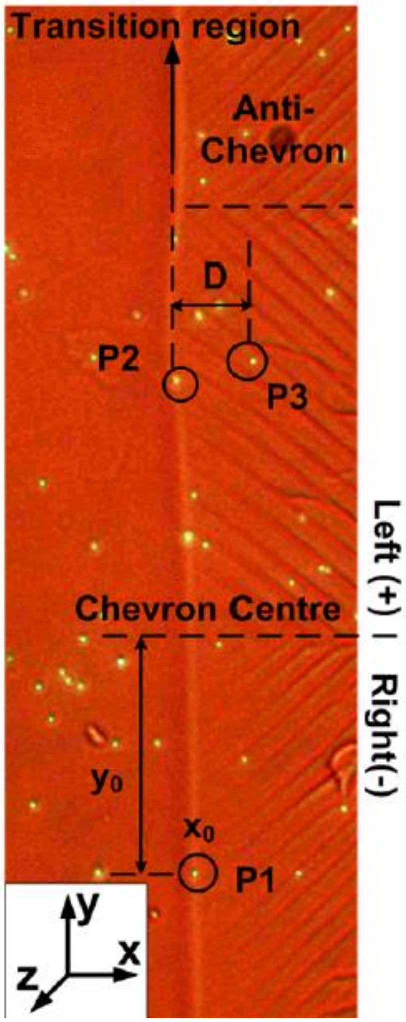
Bottom

Top

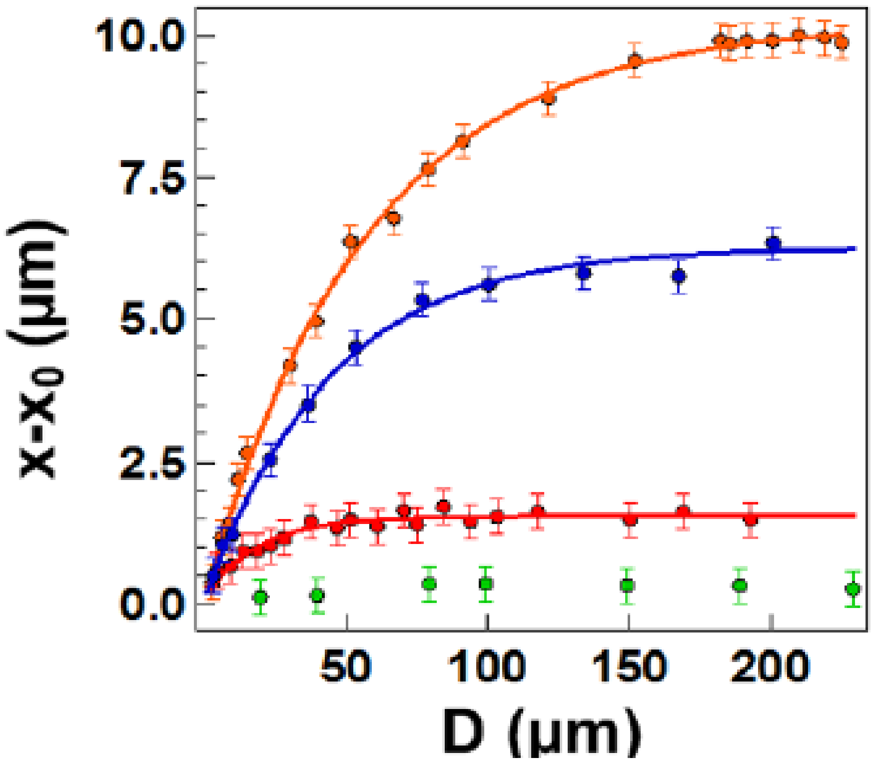
- ❑ **Band spacing depends on film yield stress**
- ❑ **Band widths and spacing vary with drying rate but obey a Lever rule**

B. Yang, J.S. Sharp, M.I. Smith ACS Nano 9:4077 (2015)

Measuring film compaction



- Fluorescent tracer particles added to suspension
- Once particles become trapped at the transition region we track their x and y coordinates
- The small subsequent movements enable us to quantify film deformation

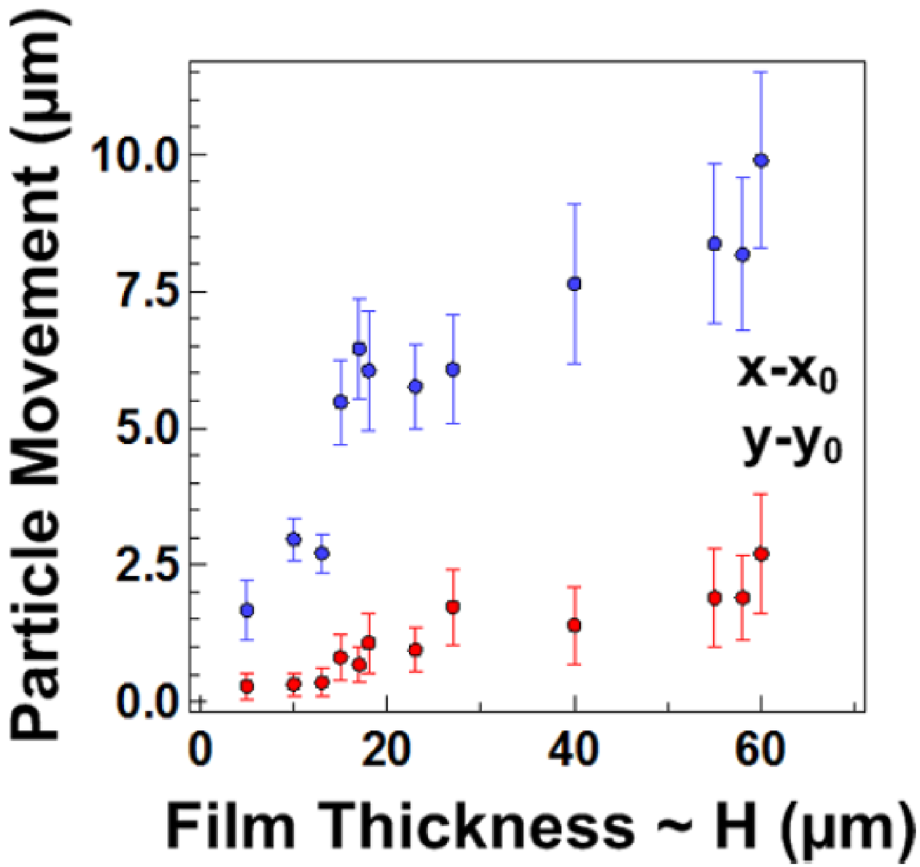


- Stress in the drying film produces compaction beyond transition region.
- Compaction is too small to measure for 200nm particles - no banding

$$dx = dx_{max}[1-\exp(-D/\lambda_{fit})]$$

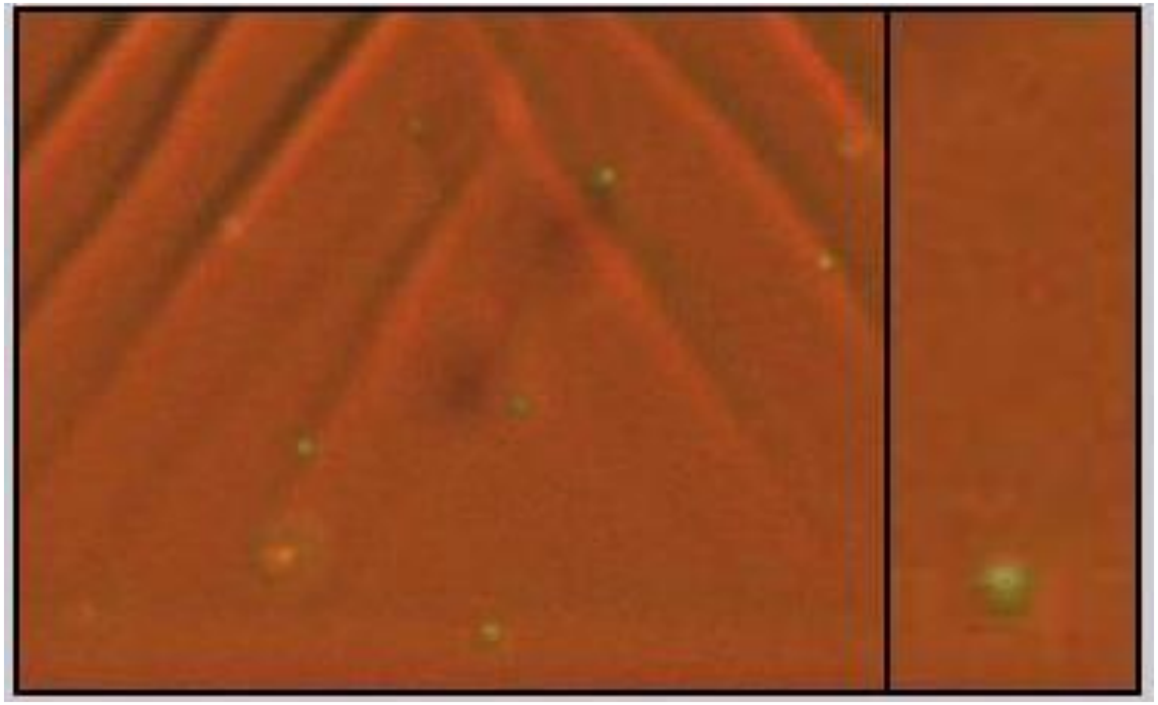
- λ_{fit} closely matches the spacing between shear bands.

→ **Suggests compaction drives shear band formation and sets lengthscale**



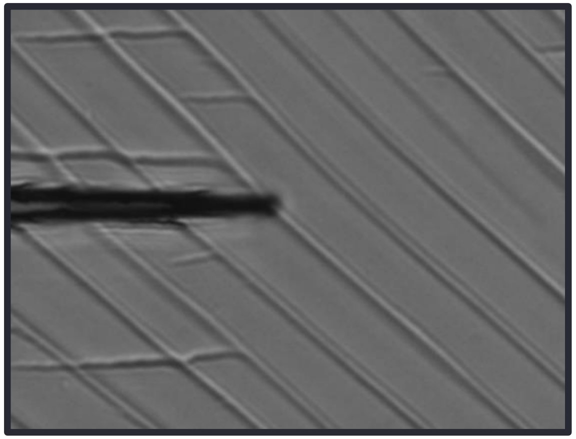
- Total movement of particles depends on film thickness.
- Consistent movement in the y direction also measurable
- Particles to the left of a chevron move left; particles to the right move right.
- y movement due to shear, x movement compaction + shear

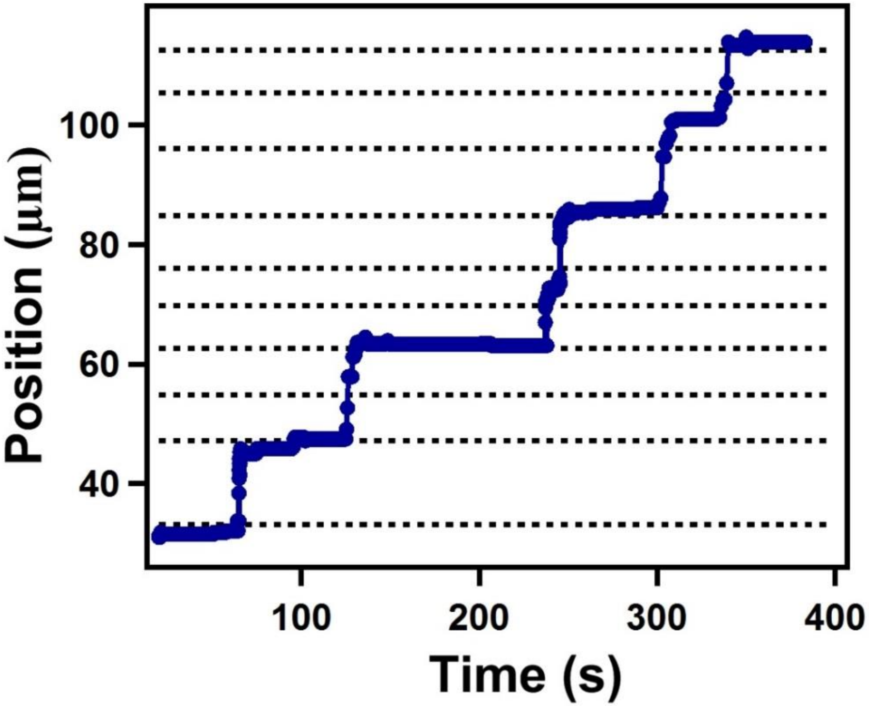
Directly observing compaction and shear banding



“Shear banding in drying films of colloidal nanoparticles”
B. Yang et al ACS Nano 9, 4077-4084 (2015)

Shear bands and crack hopping

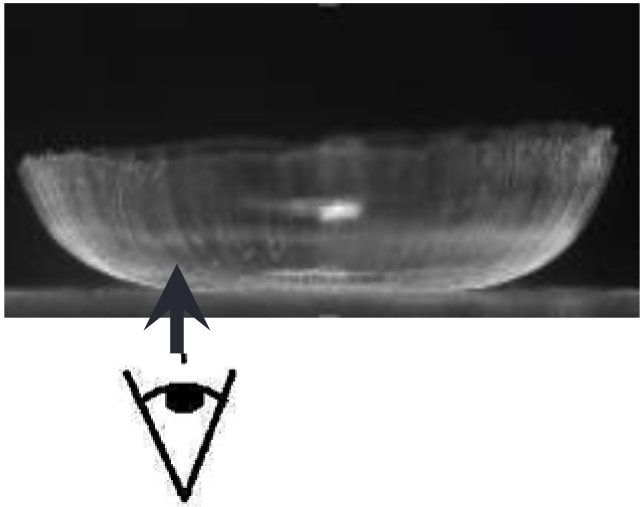


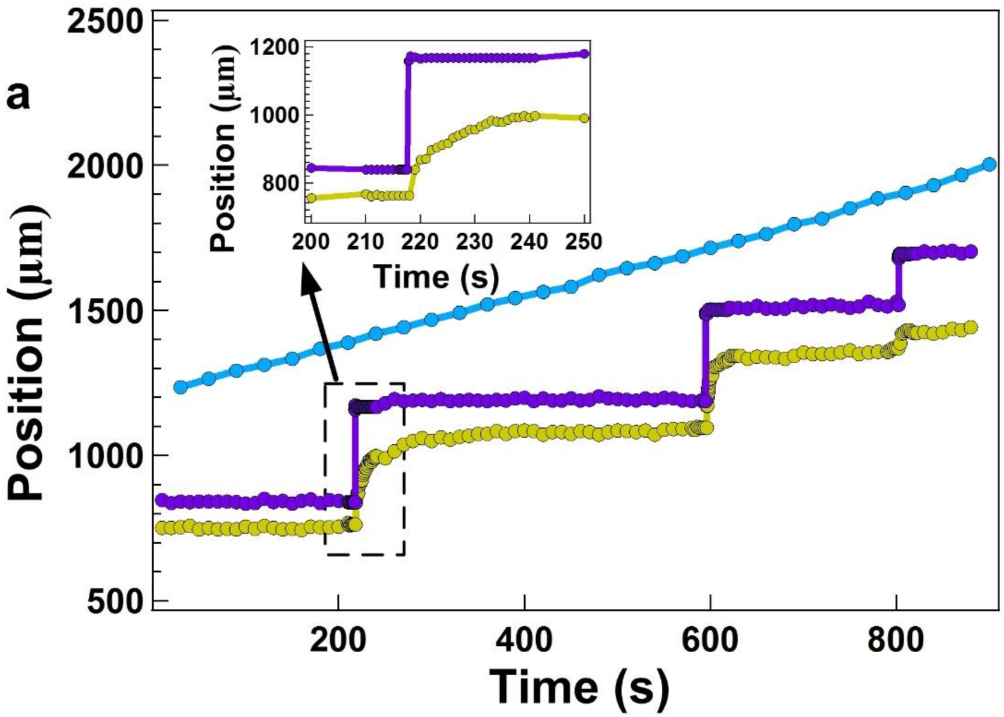


- ❑ Crack motion in a drying film often proceeds via hopping
- ❑ Crack tips hop to the location of a shear band ~ 90% of the time
- ❑ Inherent asymmetry develops

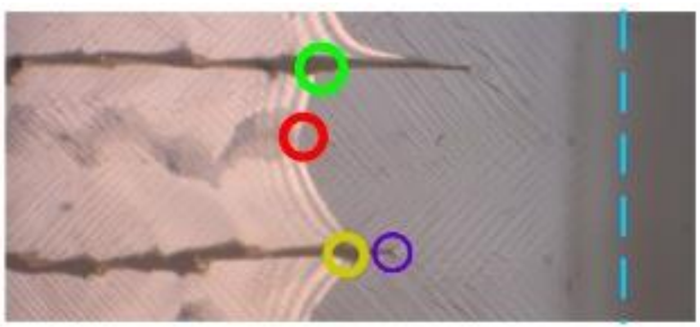
Delamination

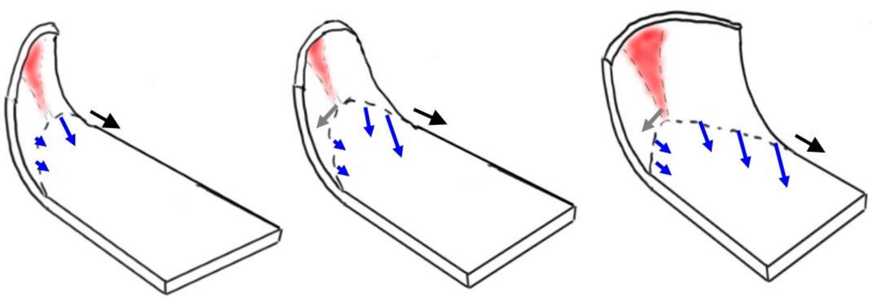
Delamination

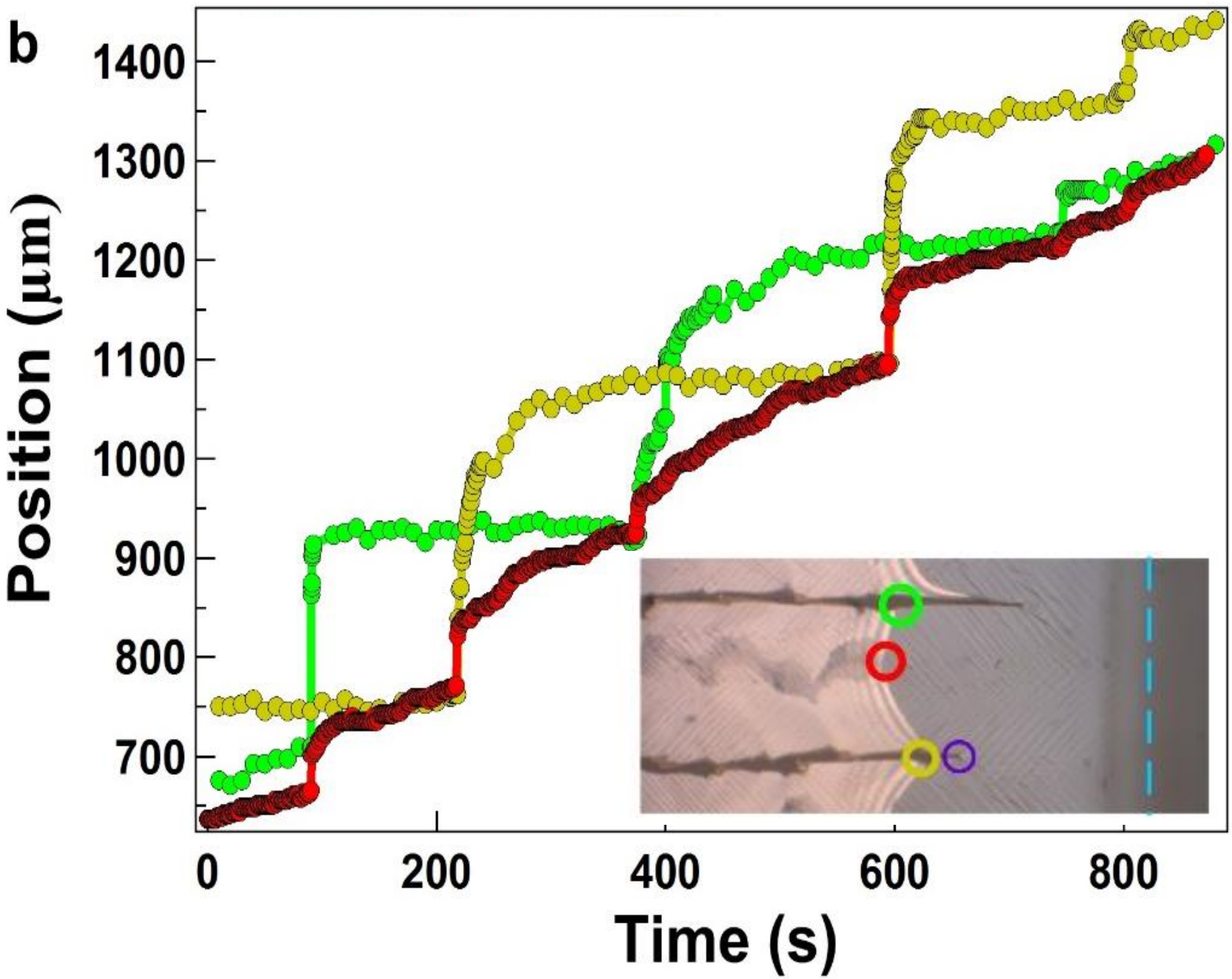




- ❑ **Crack hopping initiates delamination of the adjacent film**
- ❑ **Asymmetry of crack hops → Asymmetry delamination**

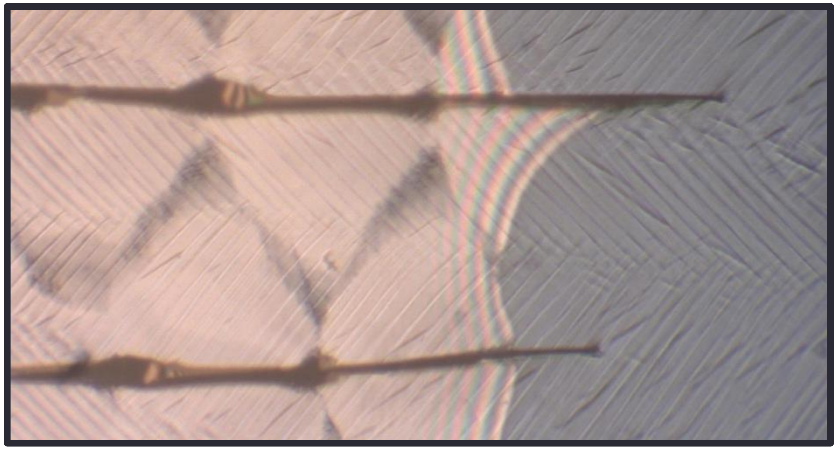


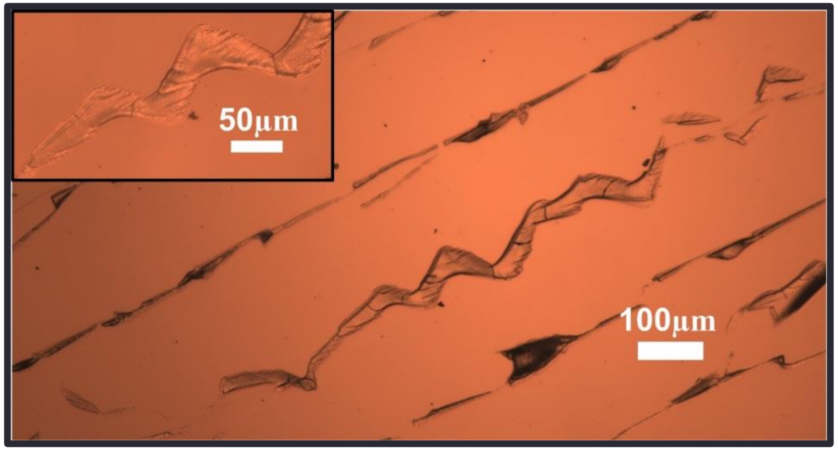




b
1400
1300
1200
1100
1000
900
800
700
Position (μm)
0
200
400
600
800
Time (s)

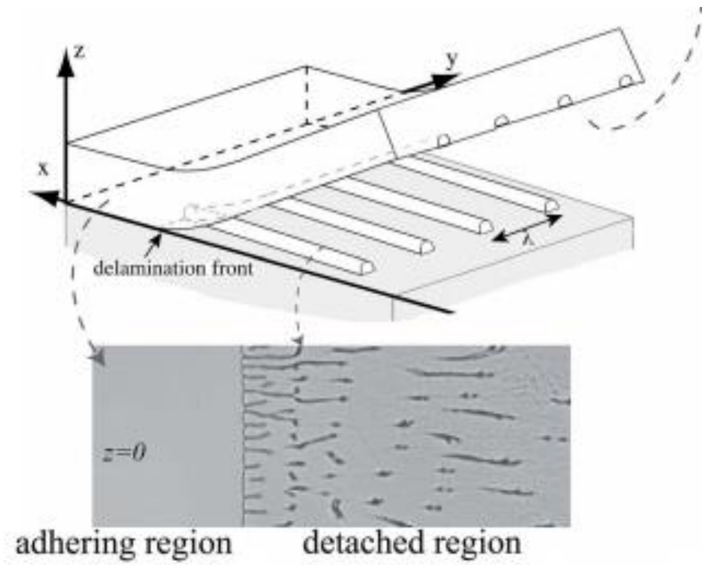
Delamination Pattern





- After film has delaminated, deposits are left behind:
  - Zig-zag pattern is a thin film deposited at the delamination front
  - Film also deposited where cracks propagate
- Always observe one pattern per cracked piece of film

Saffman Taylor Instability?

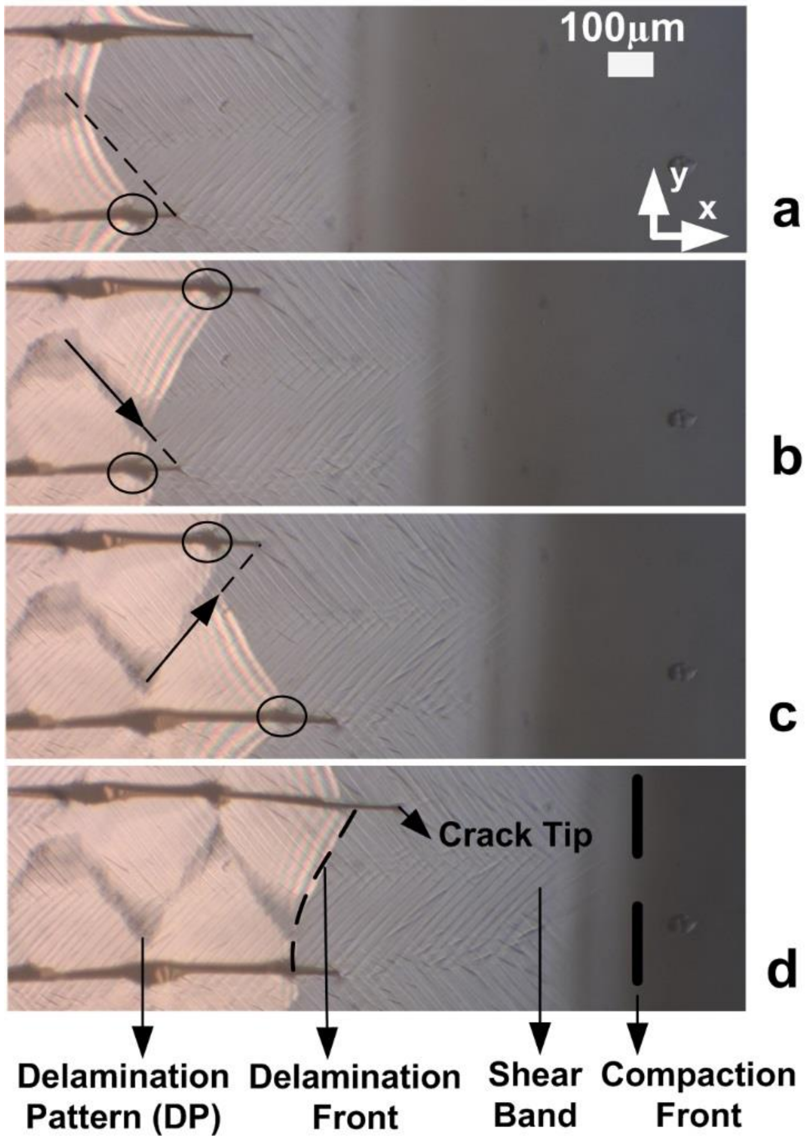


[Giorgiutti-Dauphiné et al Soft Matter 2015]

- ❑ **Lengthscale not consistent ~ 400μm**
- ❑ **1 pattern per crack regardless of spacing**

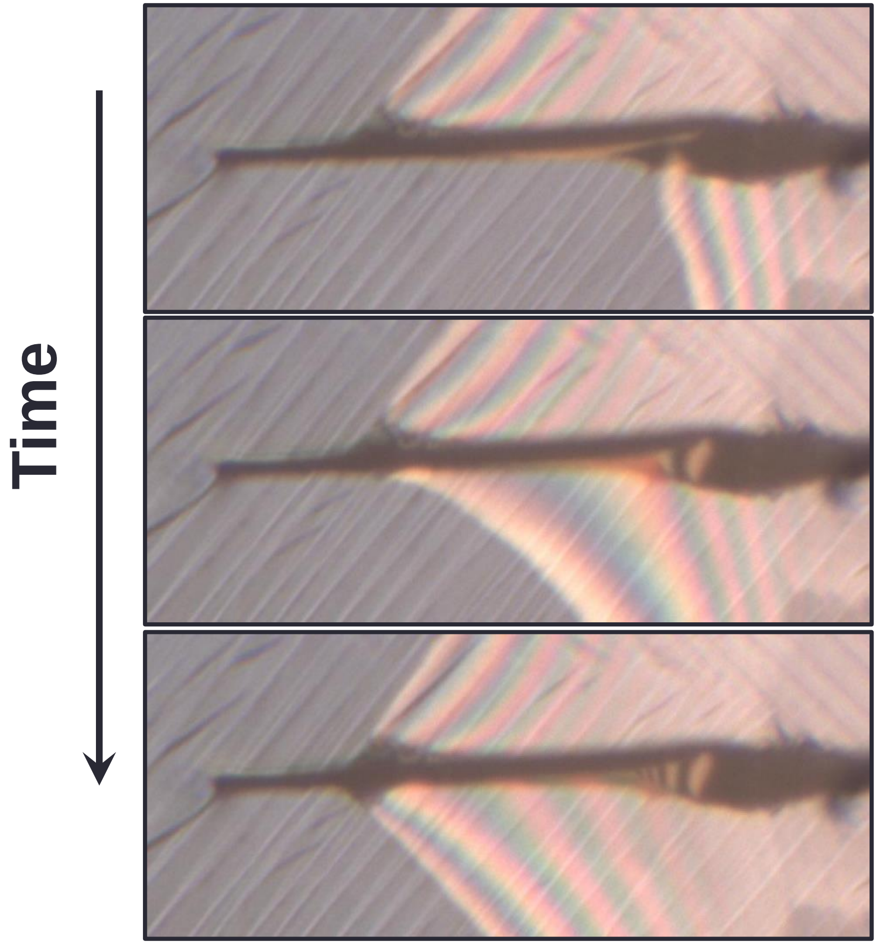
$$\boxed{\lambda \sim \xi\sqrt{\frac{\gamma}{\mu v}} \sim 4\mu\mathrm{m}}$$

Interplay of cracks with Delamination

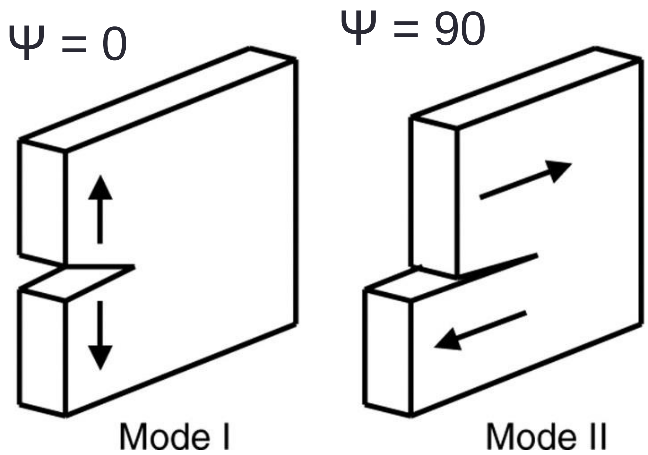


- ❑ Motion of DP is always directed towards trailing crack tip
- ❑ Asymmetry in crack hops controls course of DP

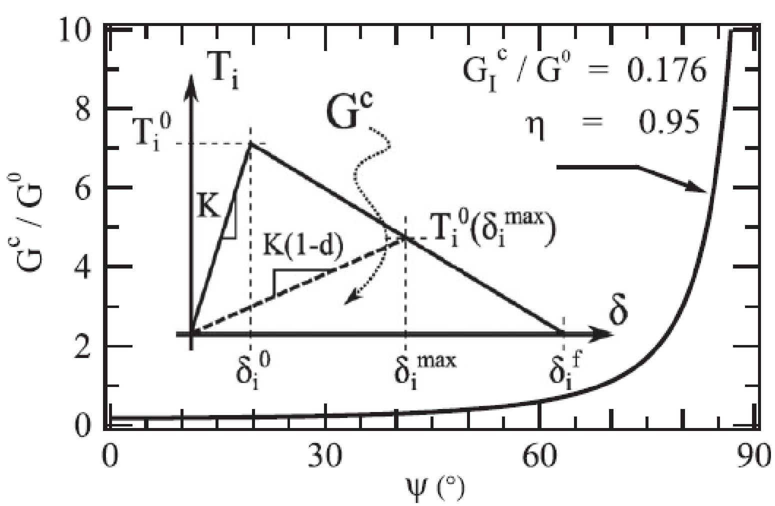
Crack opening – Shear forces

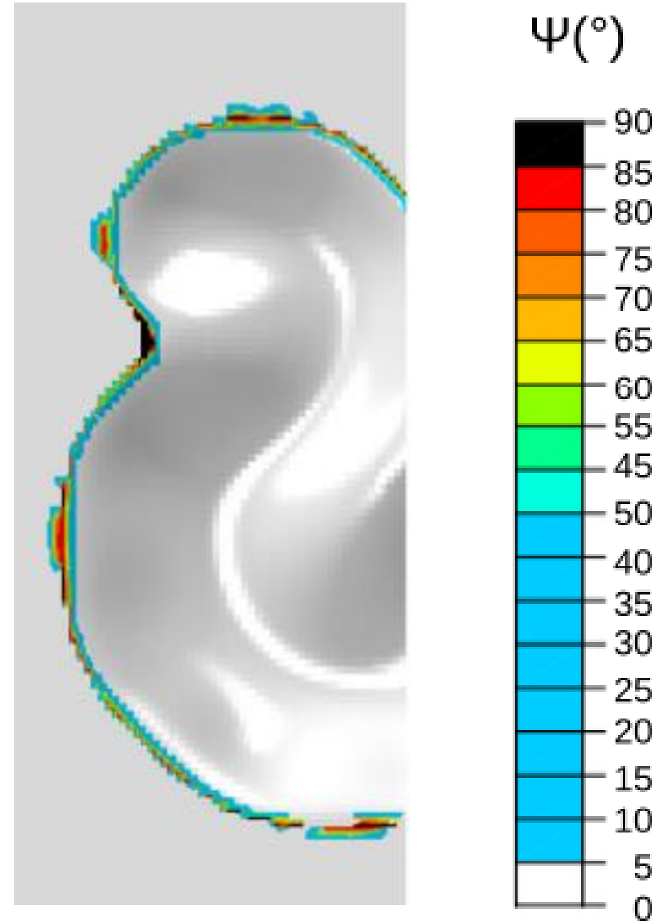


- ❑ Shape of cracks change due to delamination front
- ❑ Final shape matches deposit on surface
- ❑ Force along delamination front shears film relative to constraining substrate



Mode of crack propagation strongly work of adhesion



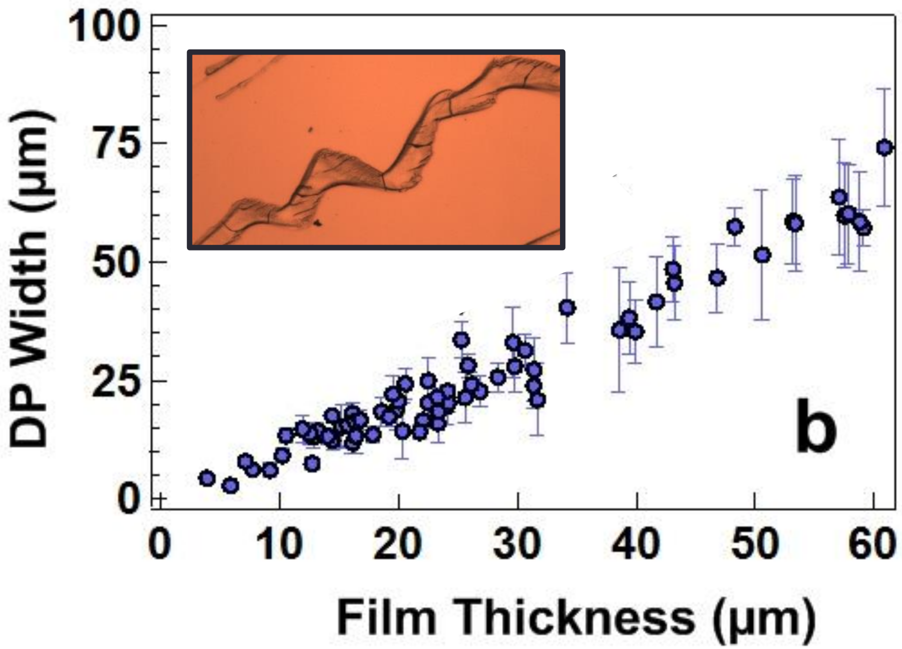


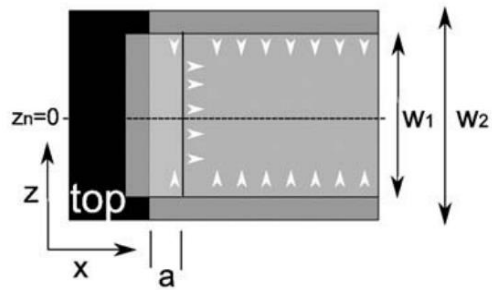
[Faou et al Phys Rev Letts 2012]

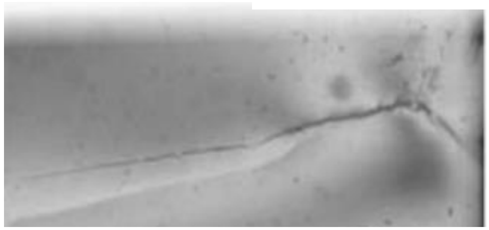
Increasing interfacial toughness leads to:

- pinning / resistance at apex delamination front
- crack kinking from interface (ie pattern deposited at interface)

See for example He, Hutchinson J. Appl. Mech. 56, 270 (1988)







Vellinga et al Thin Solid Films 2007

$$D \sim \left(\frac{E}{\sigma_0}\right)^{0.5} H$$

[Evans, Hutchinson Int. J. Solid Struct. 20, 455 (1984)]

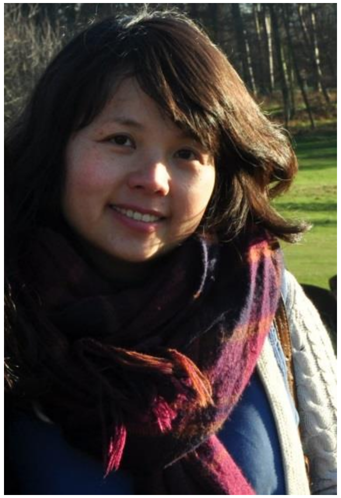
Conclusions

- Particle tracking shows that compaction after the transition region provides the driving force for shear band formation.
- There is a complex interplay between different mechanical instabilities in a drying colloidal film
- Delamination pattern occurs due to a change in the mode of interfacial crack propagation

"Shear banding in drying films of colloidal nanoparticles"
B. Yang et al ACS Nano 9, 4077-4084 (2015)

"The interplay of crack hopping, delamination and interface failure in drying nanoparticle films" B.Yang et al Sci. Reps. 6, 32296 (2016)

Acknowledgements



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