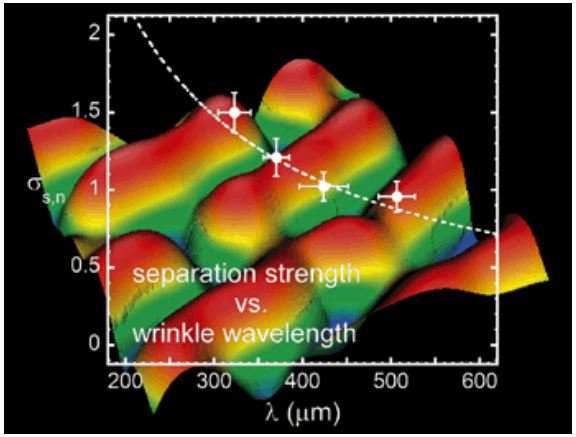
Surface Wrinkles for Controlling Soft Material Adhesion



Edwin P. Chan

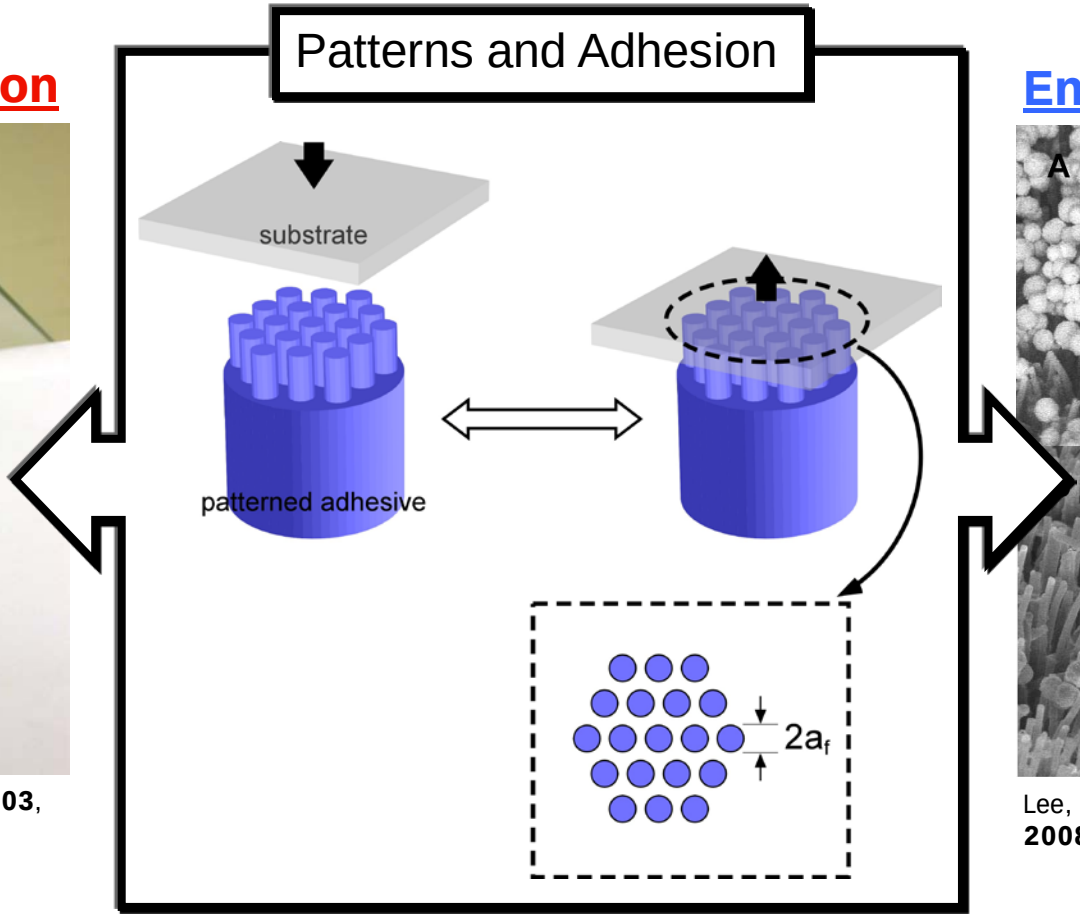
Polymers Division
National Institute of Standards and Technology
Gaithersburg, Maryland

NCMC-14 Meeting

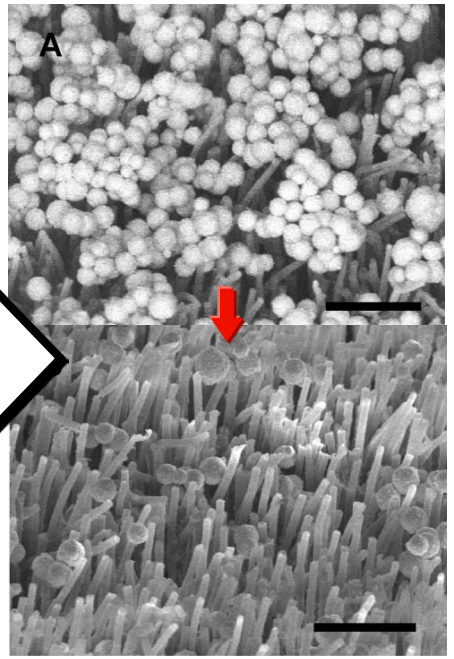
Tailoring Interfacial Properties

Enhanced adhesion

Geim, A. K. *et al.,* Nat. Mater., **2003**, 2, 461-463

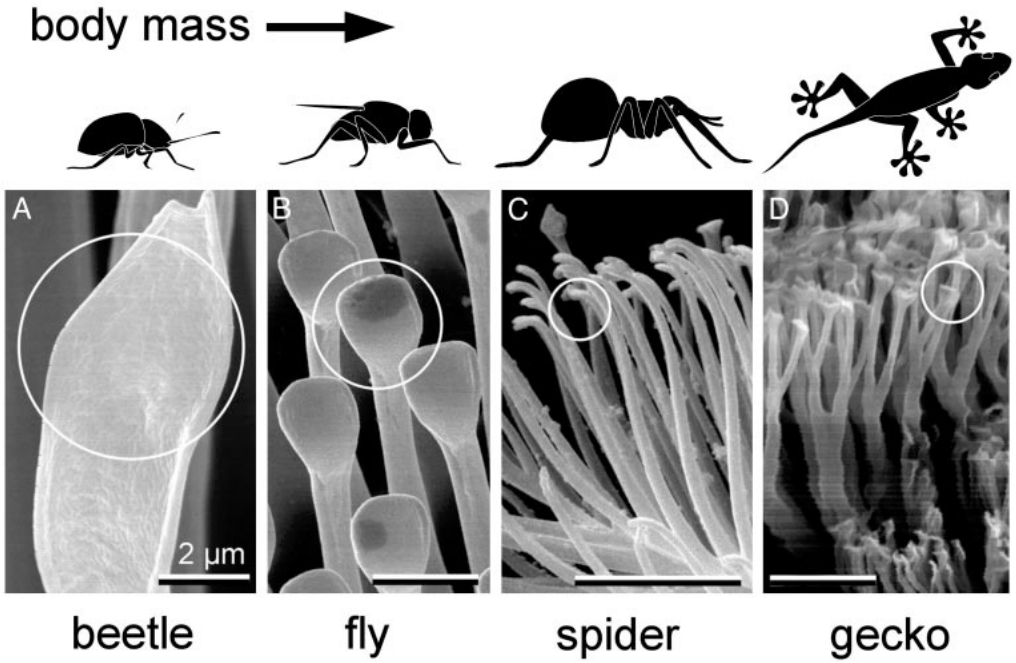


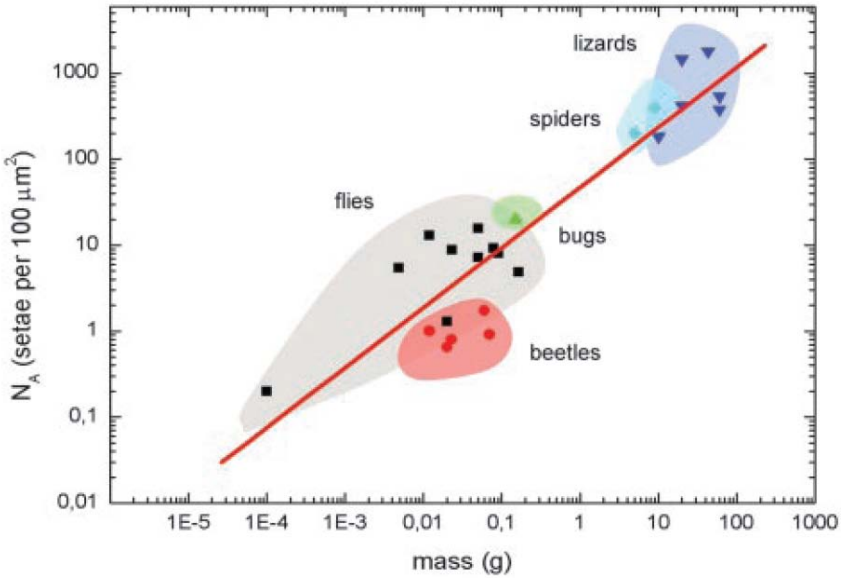
Enhanced release



Lee, J. & Fearing, R. S., Langmuir, **2008**, 24(19), 10587-10591

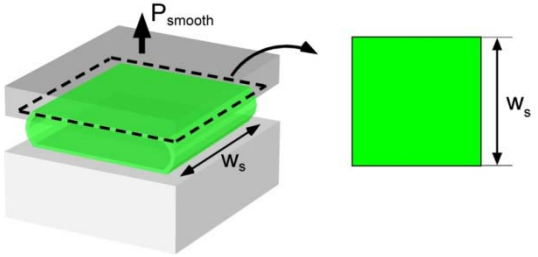
Nature's Adhesives

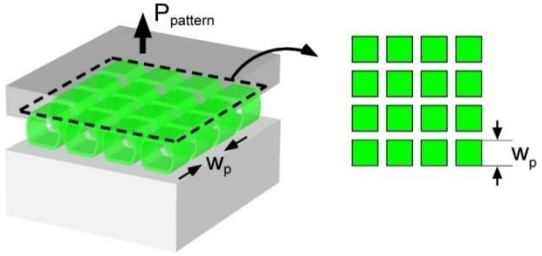




Arzt, E.; Gorb, S.; Spolenak, R. *PNAS* **2003,** 100, (19), 10603-10606

Contact Line Splitting





Separation strength:

$$\sigma_{smooth} = \frac{2 \cdot G_c \cdot w_s}{A_{projected}}$$

$$\sigma_{pattern} = \frac{n \cdot \left(2 \cdot G_c \cdot w_p\right)}{A_{projected}}$$

Equal projected contact area:

$$A_s = {w_s}^2$$

$$A_p = n\left({w_p}^2\right)$$

Normalized separation strength:

$$\frac{\sigma_{pattern}}{\sigma_{smooth}} = \frac{n \cdot w_p}{w_s}$$

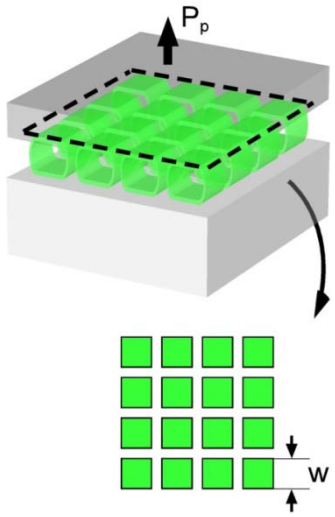
Enhancement:

$$\boxed{\frac{\sigma_{pattern}}{\sigma_{smooth}} = n^{1/2}}$$

Chan, E. P.; Greiner, C.; Arzt, E., Crosby, A. J. *MRS Bulletin*, **2007**, 32, 496-503

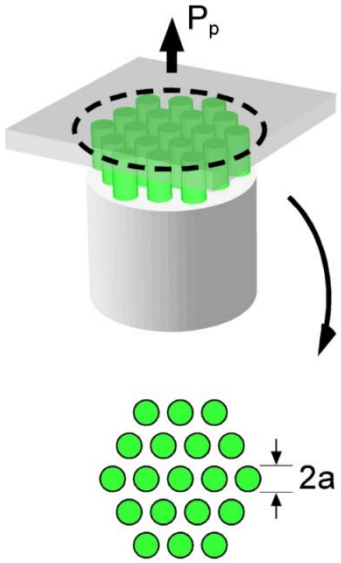
Different Contact Geometries

Tapes



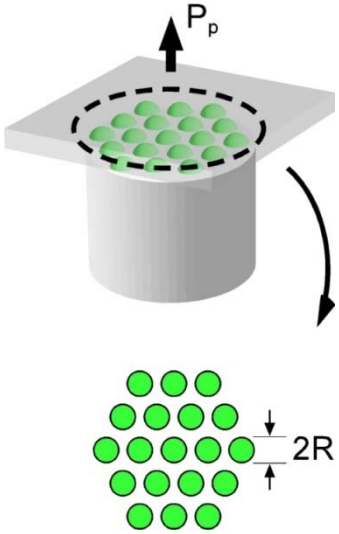
$$\frac{\sigma_{pattern}}{\sigma_{smooth}} = n^{1/2}$$

Cylinders



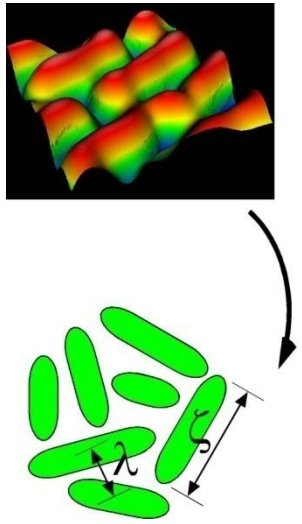
$$\frac{\sigma_{pattern}}{\sigma_{smooth}} = n^{1/4}$$

Spheres



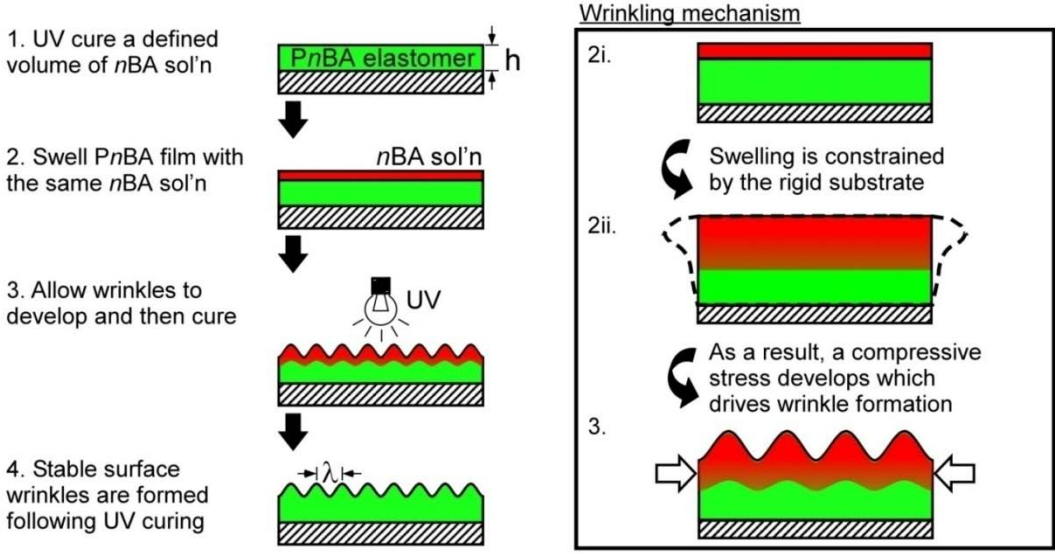
$$\frac{\sigma_{pattern}}{\sigma_{smooth}} = n^{1/2}$$

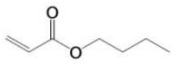
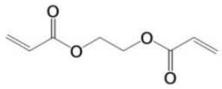
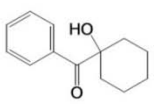
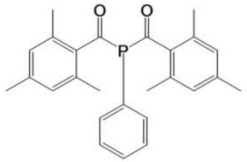
Wrinkles



Chan, E. P.; Greiner, C.; Arzt, E., Crosby, A. J. *MRS Bulletin*, **2007**, 32, 496-503

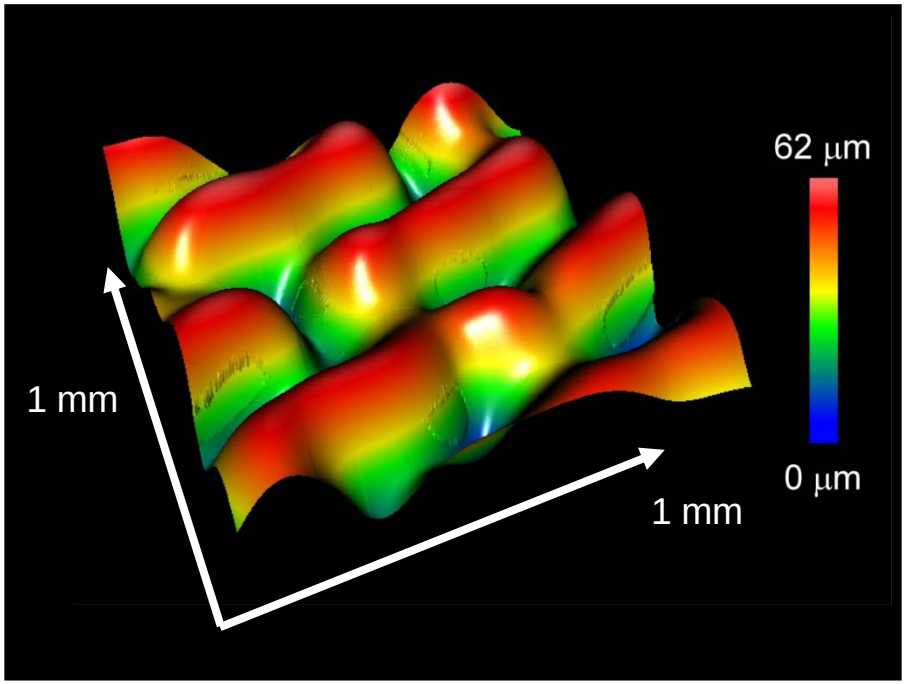
Fabricating a Wrinkled Adhesive by Swelling

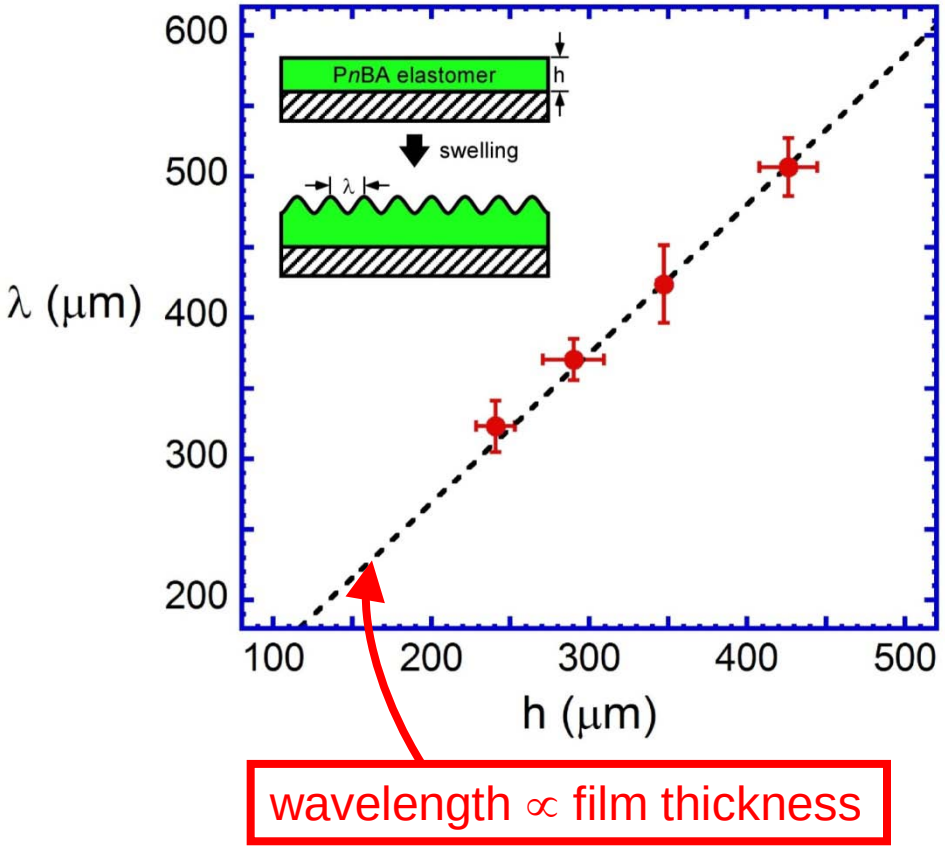


*n*BA formulation		
Monomer	Crosslinker	Photoinitiators
		 
n-butyl acrylate (~98%)	ethylene glycol dimethacrylate (~2%)	Ciba® Irgacure® 183 / Ciba® Irgacure® 819

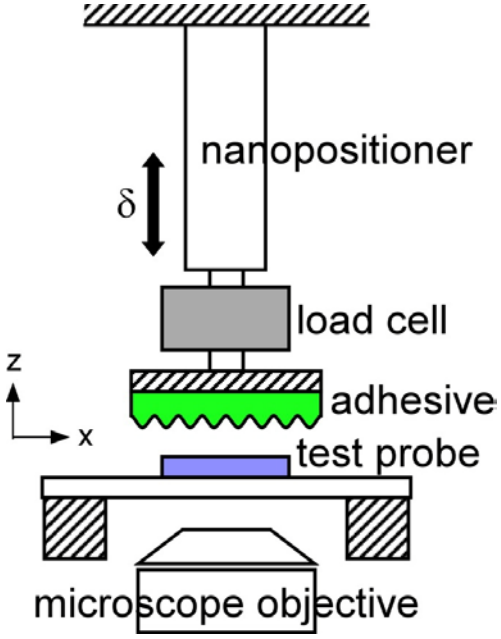
Chan, E. P.; Smith, E. J.; Hayward, R. C.; Crosby, A. J. *Advanced Materials*, **2008**, 20(4), 711-716

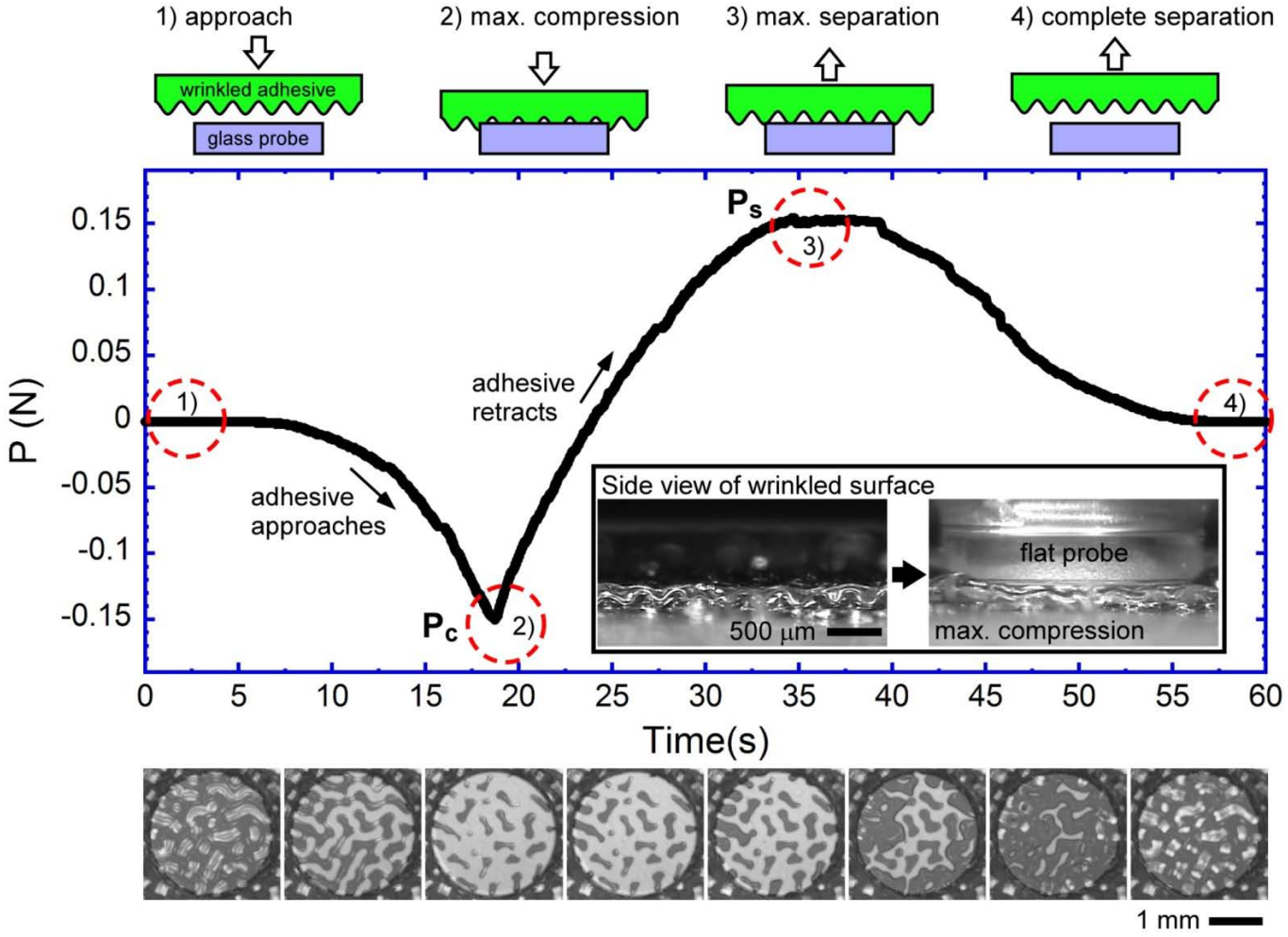
Wrinkle Wavelength (λ) Control





Measuring Adhesion

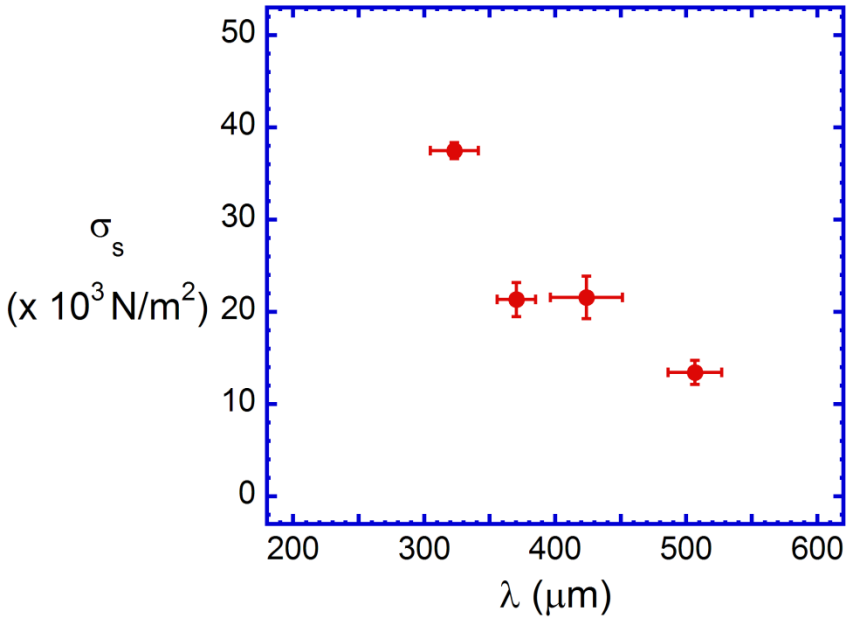




Describing Adhesion

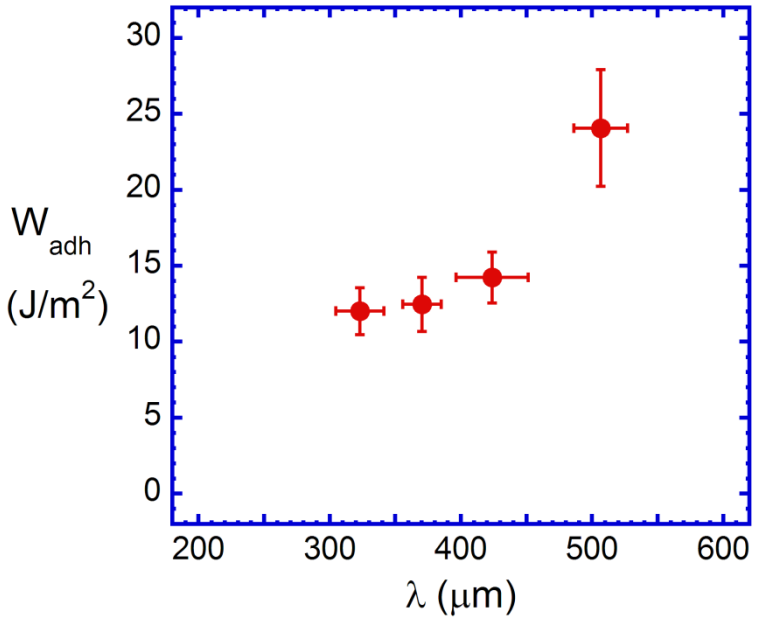
Separation strength, σ_s

$$\sigma_s = \frac{\text{separation force}}{\text{max. projected area}} = \frac{P_s}{\pi a_p^{\,2}}$$

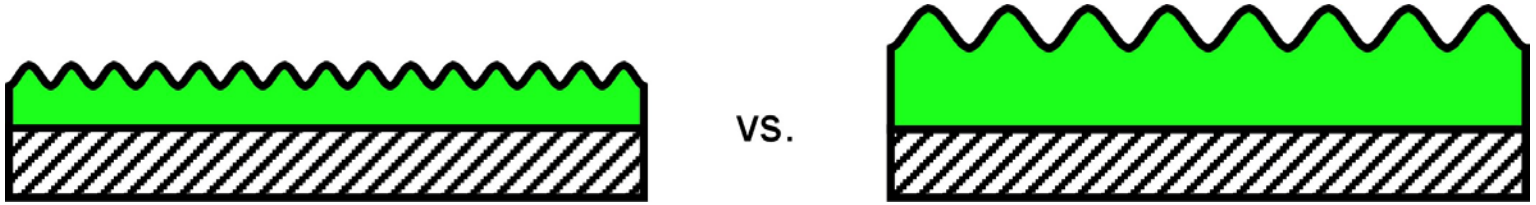


Work of adhesion, W_{adh}

$$W_{adh} = \frac{\text{separation energy}}{\text{max. projected area}} = \frac{\int P \cdot \partial\delta}{\pi a_p^{\,2}}$$



Contributions to Enhancement



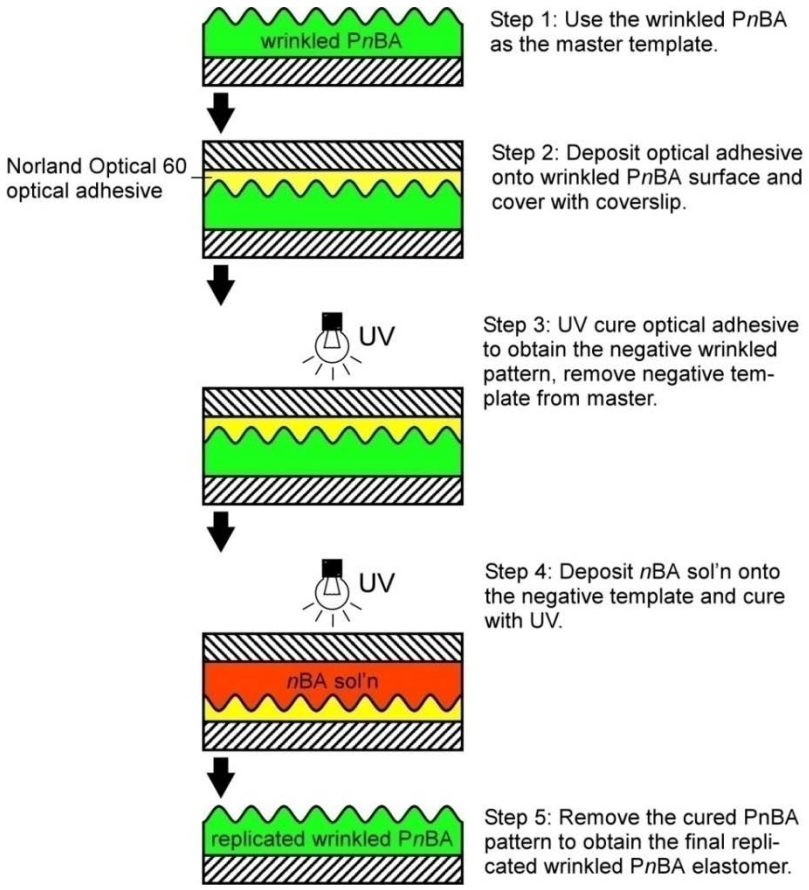
1. Geometry of the wrinkle pattern
   - control of adhesion by contact splitting (λ)

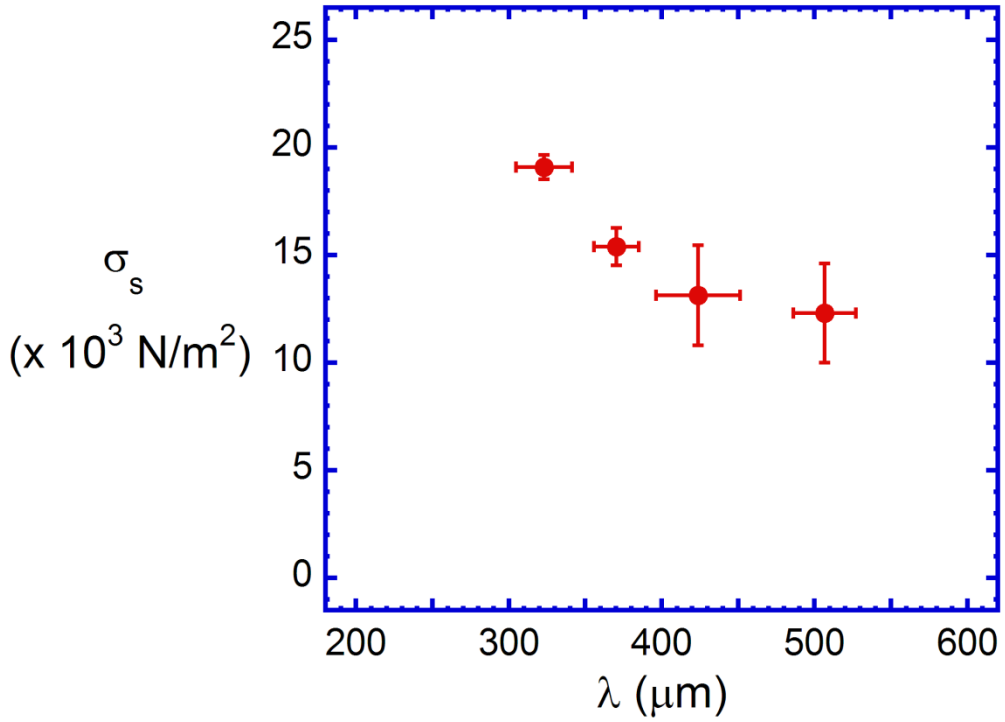
2. Changes in the P*n*BA film thickness*
   - changes in the debonding mechanism due to lateral confinement effects (recall that $\lambda \propto h$)

3. Tuning of P*n*BA material properties due to swelling
   - differences in elastic modulus (E) and adhesion energy (G_c)

*Crosby, A.J. *et al.*, *J. Appl. Phys.* **2000**, 88, 2956-2966

Adhesion of Replicated Wrinkles: Wavelength Control of Adhesion

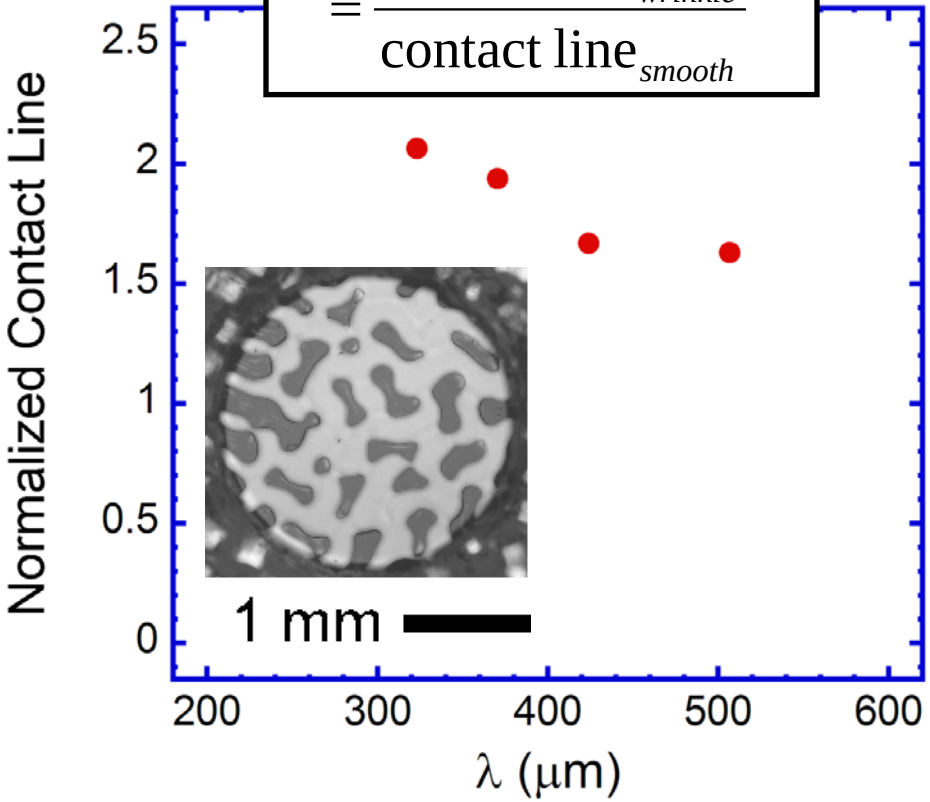


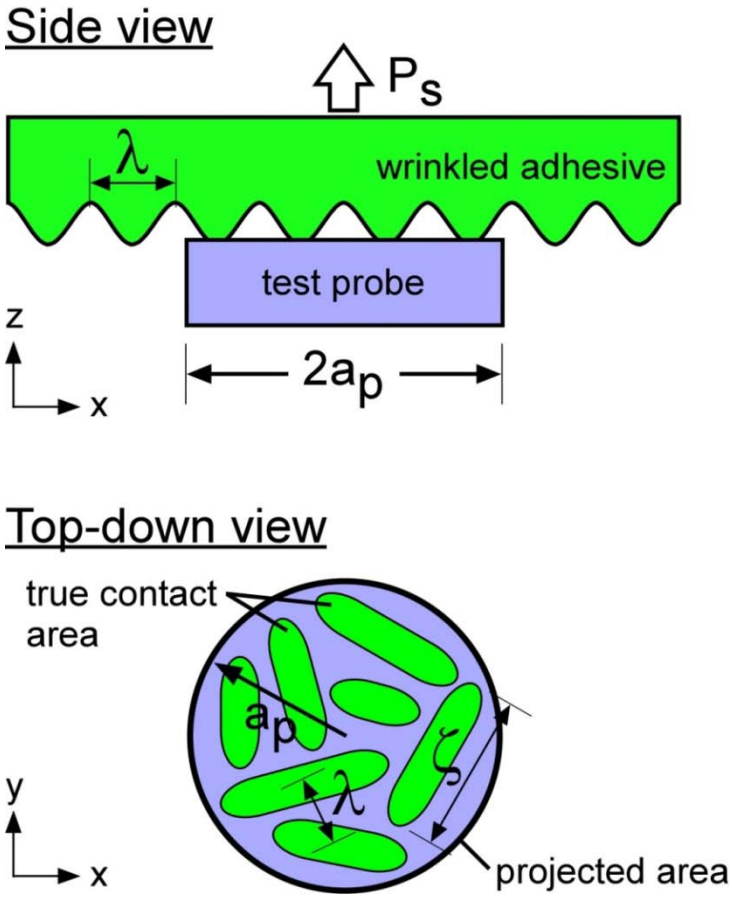


Chan, E. P.; Smith, E. J.; Hayward, R. C.; Crosby, A. J. *Advanced Materials*, **2008**, 20(4), 711-716

Contact Line Splitting for Wrinkles

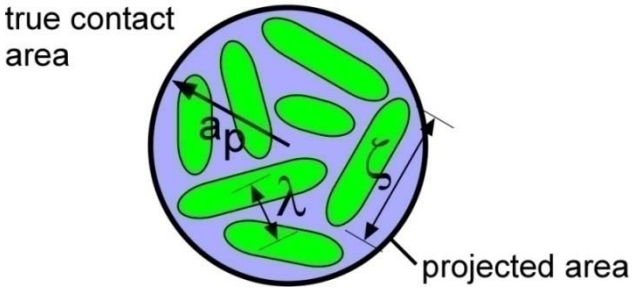
$$\text{Normalized contact line} = \frac{\text{contact line}_{wrinkle}}{\text{contact line}_{smooth}}$$





Scaling Relationships

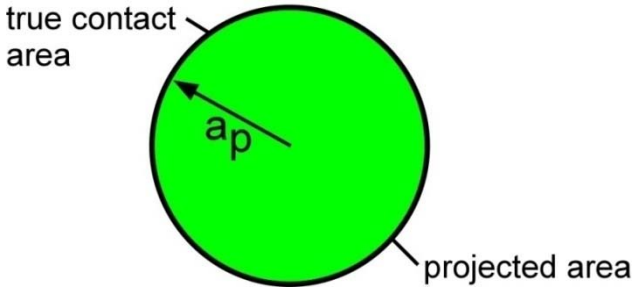
Wrinkled interface



$$\sigma_{s,w} = \frac{n \cdot \left(G_c\left(\lambda + 2\zeta\right)\right)}{\pi a_p{}^2}$$

$$= \frac{\left(\frac{\pi a_p{}^2}{\zeta\lambda}\right) \cdot \left(G_c\left(\lambda + 2\zeta\right)\right)}{\pi a_p{}^2} = \left(\frac{1}{k_1} + 2\right) \cdot \frac{G_c}{\lambda}$$

Smooth, non-patterned interface



$$\sigma_{s,s} = \frac{\left(8\pi G_c E^* a_p{}^3\right)^{1/2}}{\pi a_p{}^2}$$

$$= \left(\frac{8E^* G_c}{\pi a_p}\right)^{1/2}$$

Normalized strength:

$$\overline{\sigma}_s = \frac{\sigma_{s,w}}{\sigma_{s,s}} = \left(\left(1 + \frac{1}{2k_1}\right) \cdot \left(\frac{\pi}{2}\right)^{1/2}\right) \cdot \left(\frac{G_c}{E^*} a_p\right)^{1/2} \cdot \frac{1}{\lambda}$$

Critical Wrinkle Length Scale (λ_c) for Controlling Adhesion

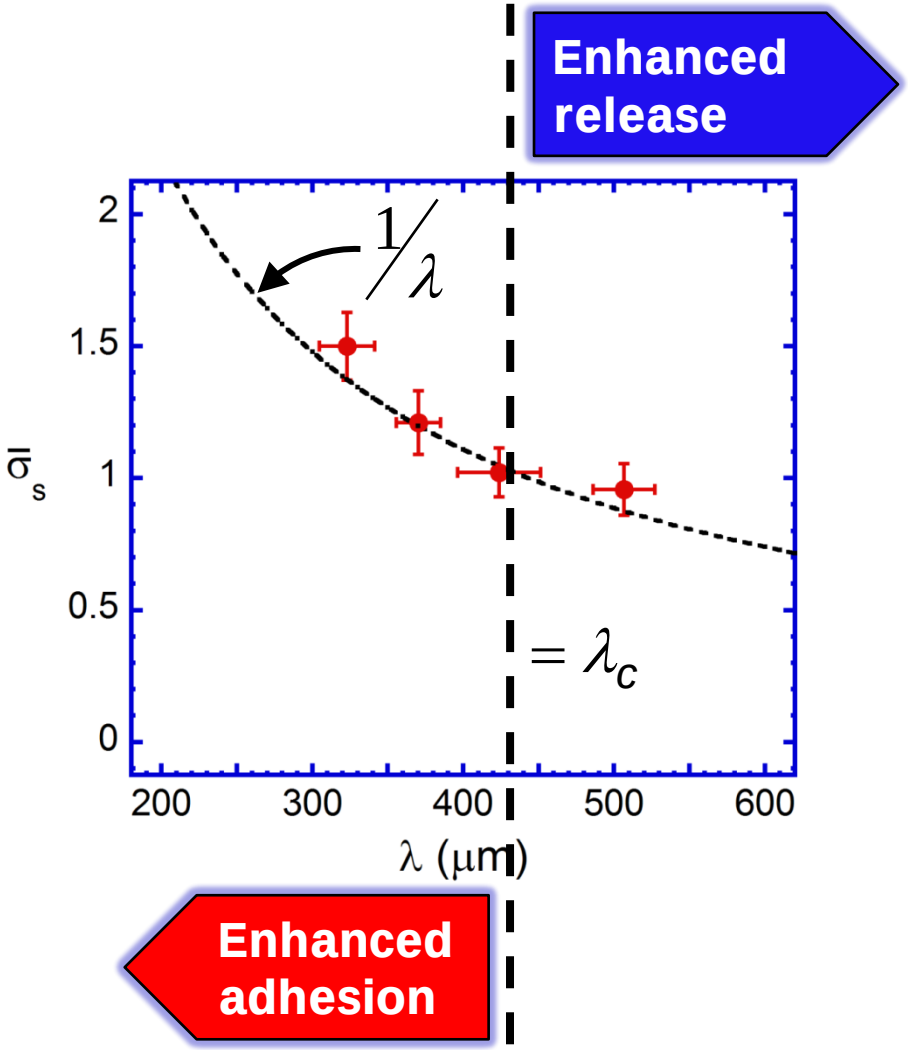
$$\overline{\sigma}_s = \left(\left(1+\frac{1}{2k_1}\right)\cdot\left(\frac{\pi}{2}\right)^{1/2}\right)\cdot\left(\frac{G_c}{E^*}a_p\right)^{1/2}\cdot\frac{1}{\lambda}$$

$$\lambda_c = \left(\left(1+\frac{1}{2k_1}\right)\cdot\left(\frac{\pi}{2}\right)^{1/2}\right)\cdot\left(\frac{G_c}{E^*}a_p\right)^{1/2}$$

From contact adhesion tests:

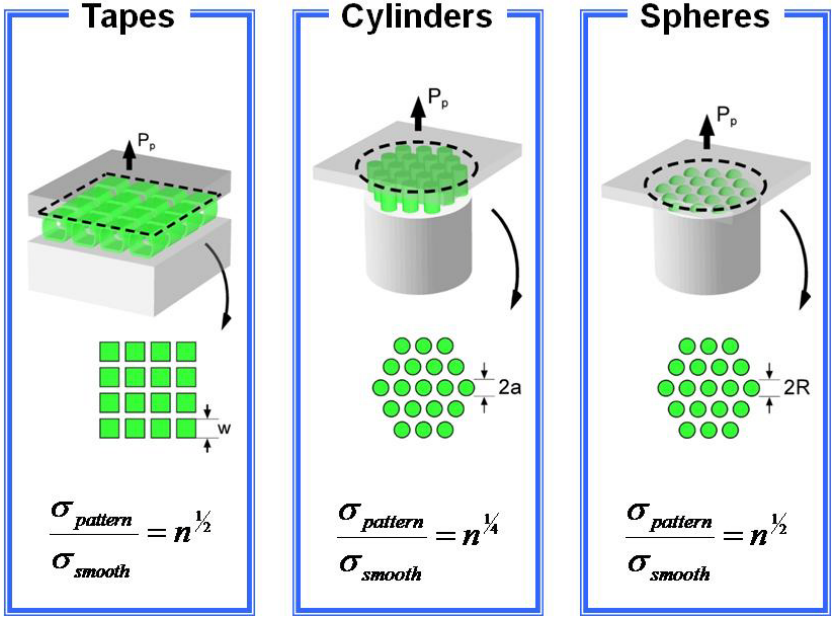
G_c = 0.6 J/m^2
E^* = 1.2 x 10^5 N/m^2
a_p = 1.2 mm
assume, k_1 ~ 1

➔ $\lambda_c \approx$ 150 μm

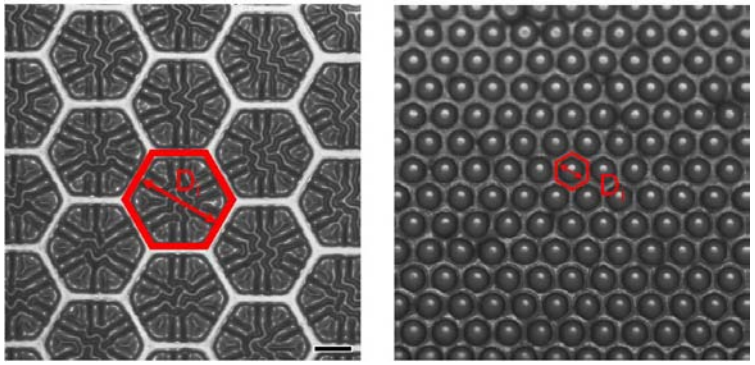


Wrinkle Pattern Control of Adhesion

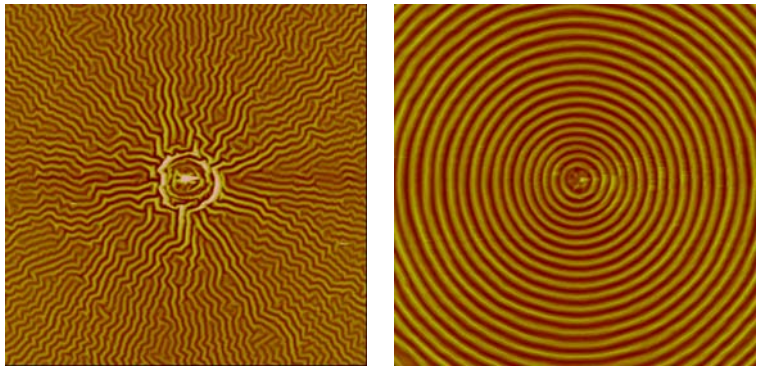
Since pattern morphology can tailor adhesion…



… surface wrinkles can provide a simply approach to access different patterns.

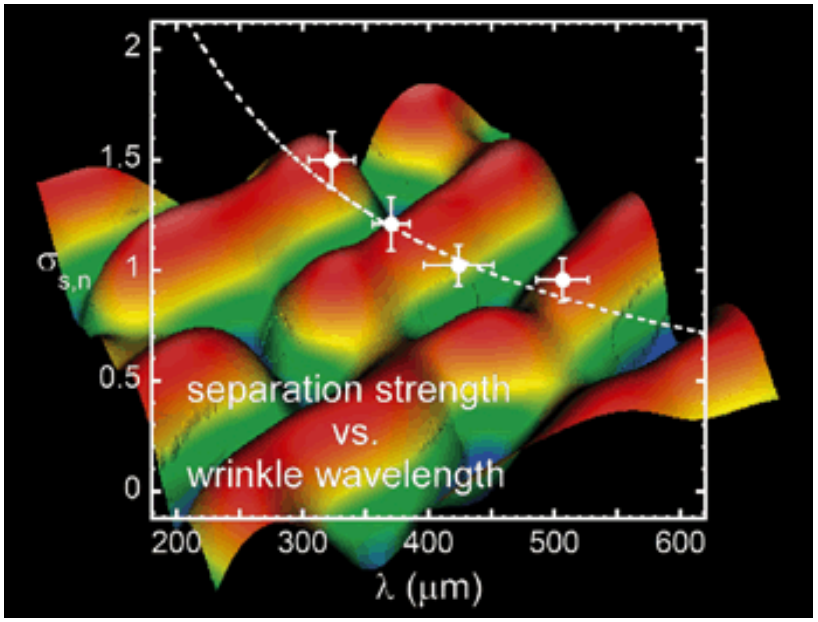


Chan, E. P.; Crosby, A. J. *Advanced Materials* **2006**, 18 (24), 3238-3242



Chung, J. Y.; Nolte, A. J.; Stafford C. M., **2008** (submitted)

Summary



- Surface wrinkling provide a “self-assembled” means to generate a patterned adhesive
- A patterned interface can enhance adhesion by increasing contact line/area
- The adhesion of the wrinkled surface is materials-defined (λ, G_c, E)
- Process is quite general and applicable to a broad range of polymers
  ➔ swelling of a polymer

Acknowledgements

Mentors:

- Prof. Alfred J. Crosby (Univ. of Mass. Amherst)
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- Prof. Robert Y. Lochhead (Univ. of So. Miss.)

Polymers Division, NIST:

- Dr. Jun Young Chung
- Dr. Adam Nolte

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