The 19th Int This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. Symposium
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Effect of blade-tip shape on the doctoring step in gravure printing processes

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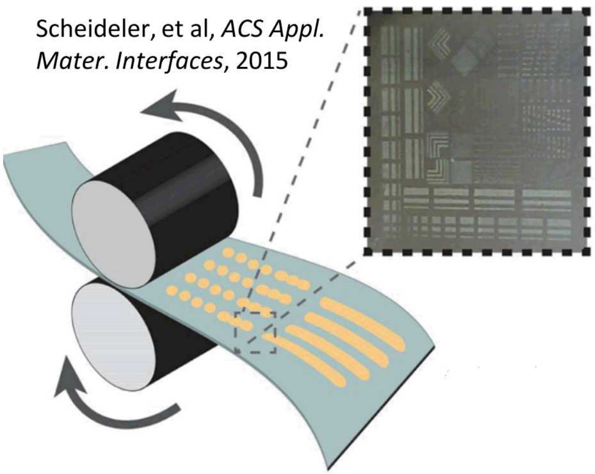
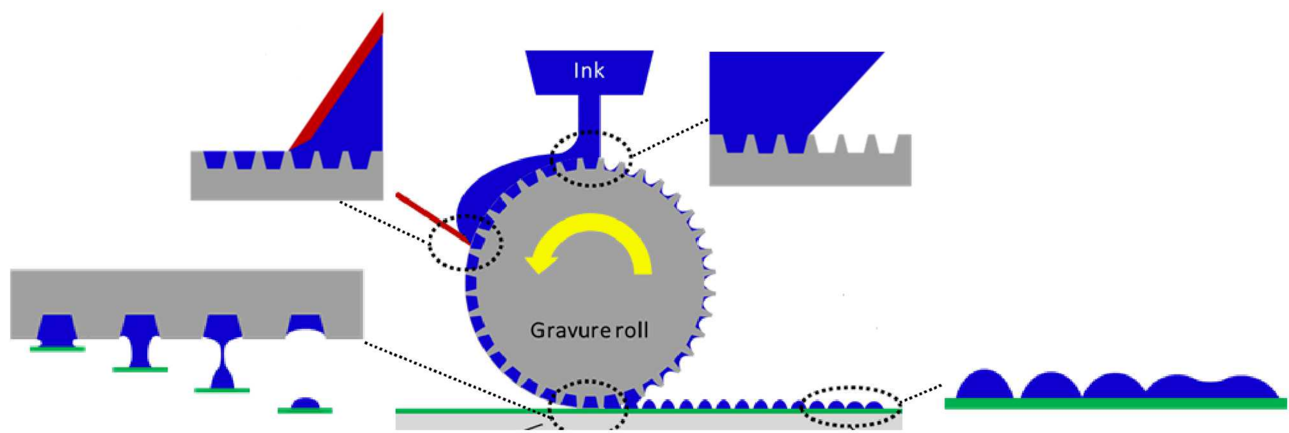
Scheideler, et al, *ACS Appl. Mater. Interfaces*, 2015





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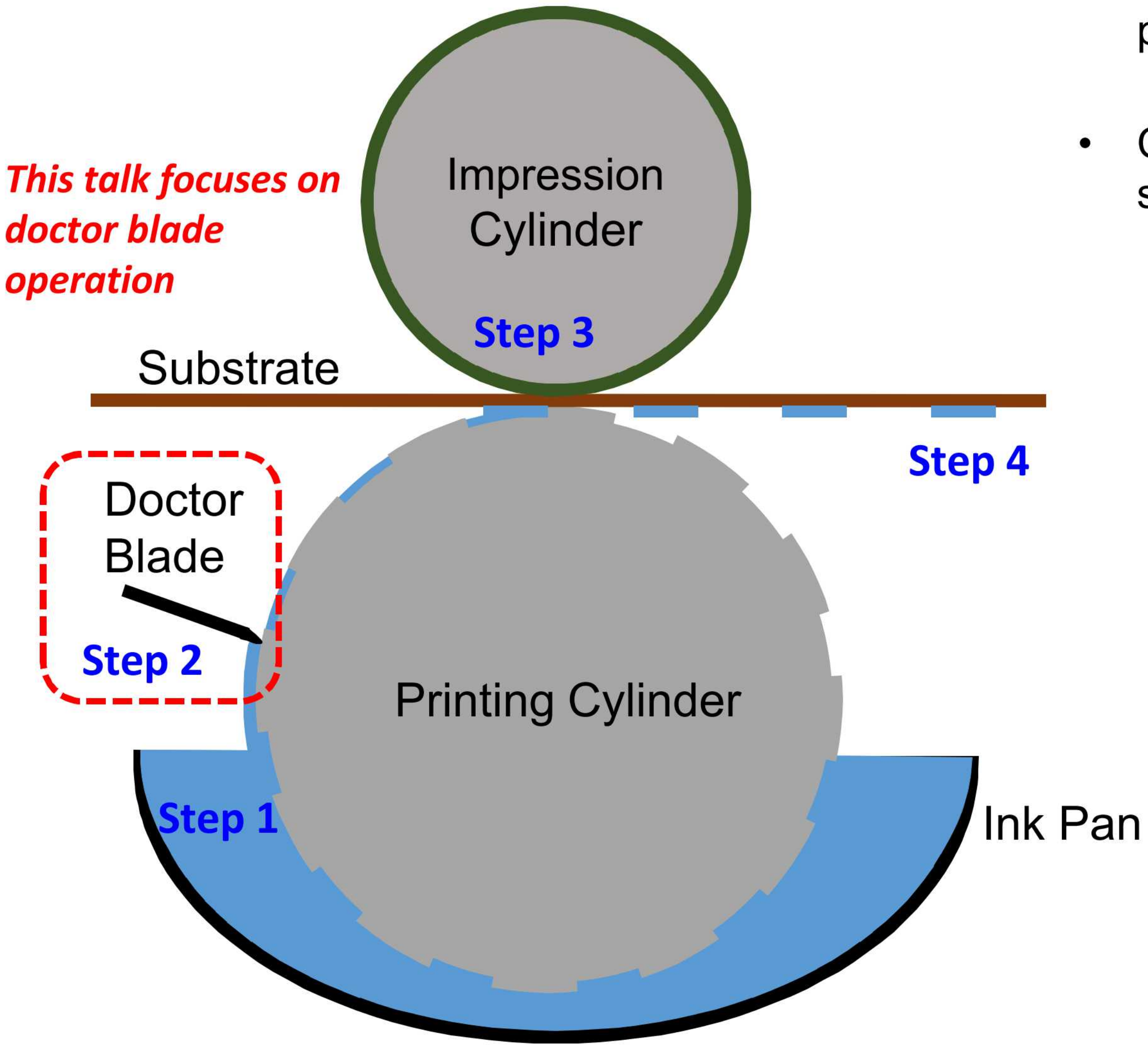
Gravure Printing



- An intaglio printing method – pattern is engraved in the roll
- Continuous roll-to-roll or roll-to-sheet process

Steps in gravure printing

1. **Fill cells with ink**
2. **Wipe away excess ink – ideally to zero thickness**
3. **Transfer onto substrate**
4. **Solidify ink**

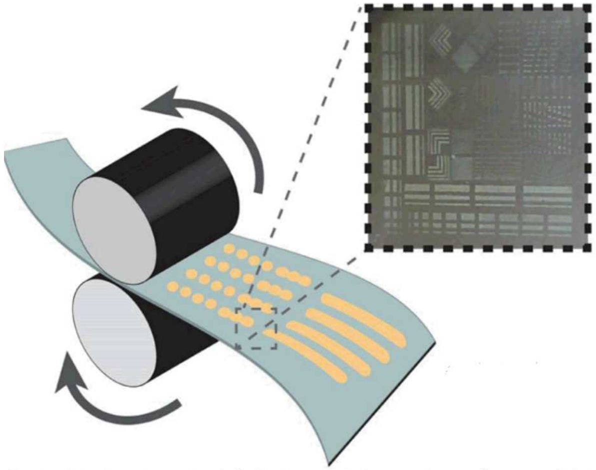
Applications of Gravure Printing

Traditional

http://www.zx-printing.com/support/magazine-printing.html

https://indonesia.deviantart.com/art/Dji-Sam-Soe-9306506

Emerging



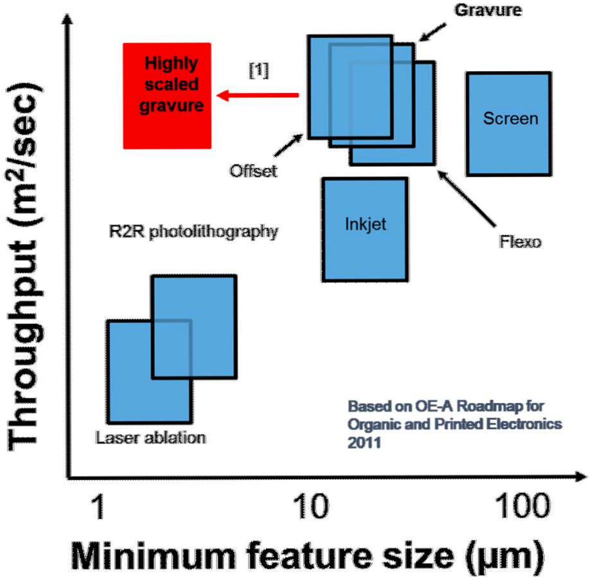
Scheideler, et al, *ACS Appl. Mater. Interfaces*, 2015

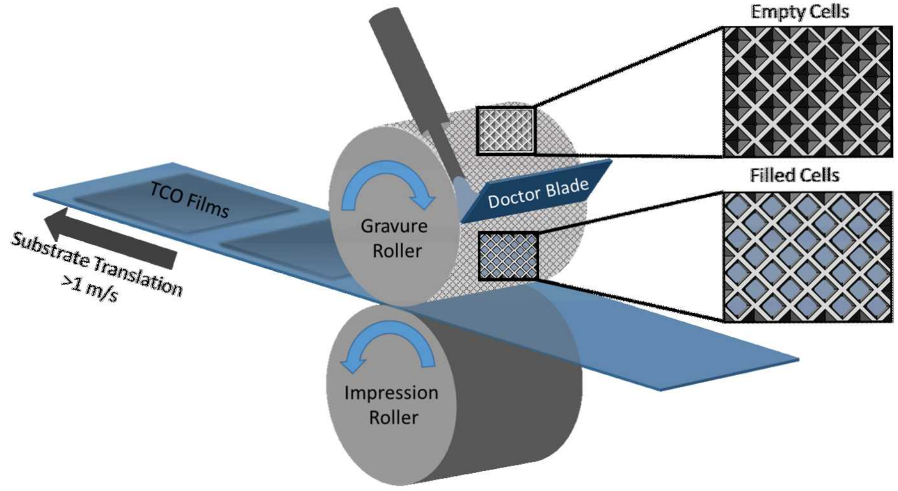
Resolution requirement :
Residual film thickness
50 µm → sub-1 µm

Key step: Doctor blade

http://solarindustrymag.com/midsummer-develops-sputtering-process-for-cigs-solar-cells-on-stainless-steel

Comparison with Other Methods





G. Grau, et. al, *Adv. Elect. Mater.*, 2016

	μ-Gravure	Inkjet
Resolution	< 5 μm	< 30 μm
Speed	1-10 m/s	< 1m/s
Ink Viscosity	1-500 cP	1-25 cP
Method	Contact	Non-Contact

Courtesy of Will. Scheideler

μ-gravure printing is most promising in terms of speed and feature scale

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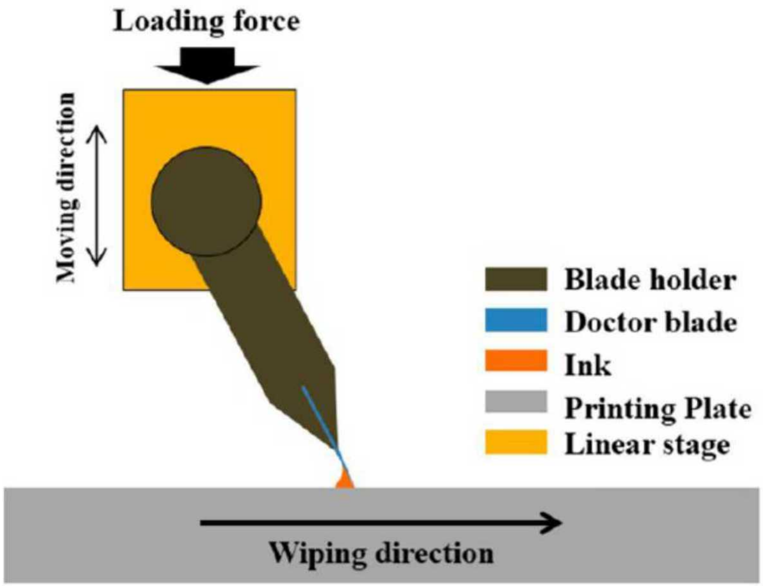
Doctoring Physics of μ-Gravure Printing

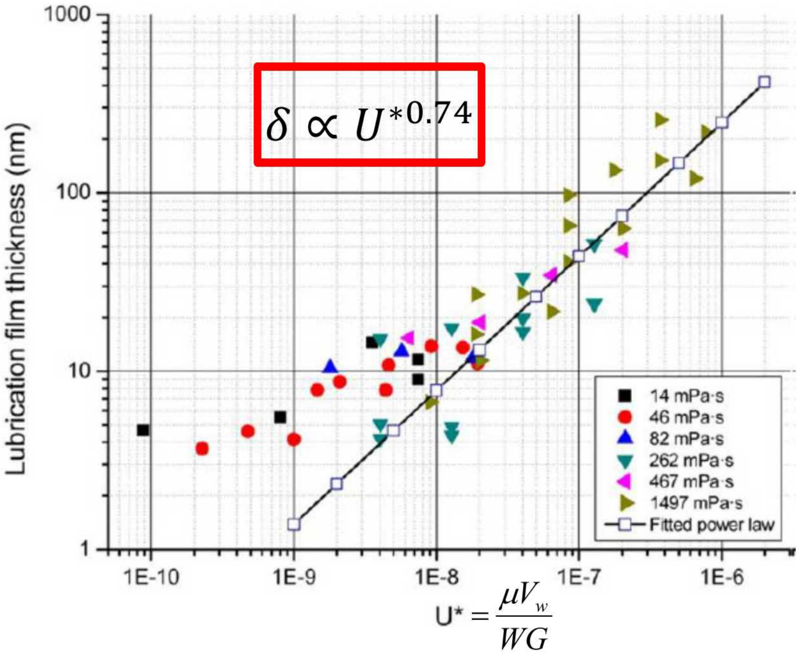
Kitsomboonloha and Subramanian *Langmuir* 2014

Experimental setup

Doctor blade over smooth plate – no printing



Residual film thickness versus wiping speed

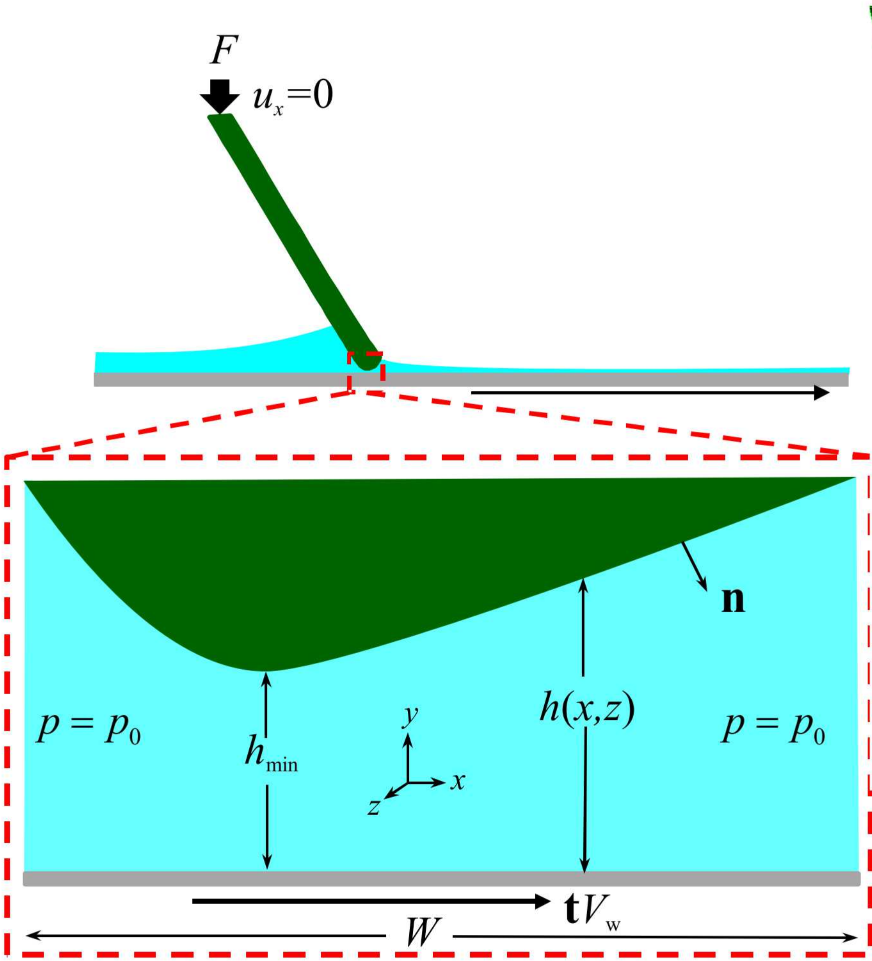


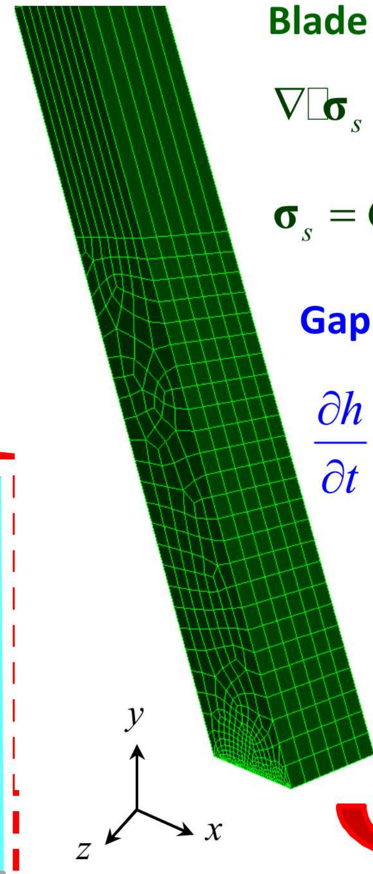
Lubrication theory Only

$$\delta = \frac{Q}{V_w} = \frac{1}{2}\frac{\int_{-w/2}^{w/2} h^{-2}(x')dx'}{\int_{-w/2}^{w/2} h^{-3}(x')dx'}$$

Function of blade shape only, no speed dependence
→ ***need to include elasto-hydrodynamic interaction***

Doctoring Model





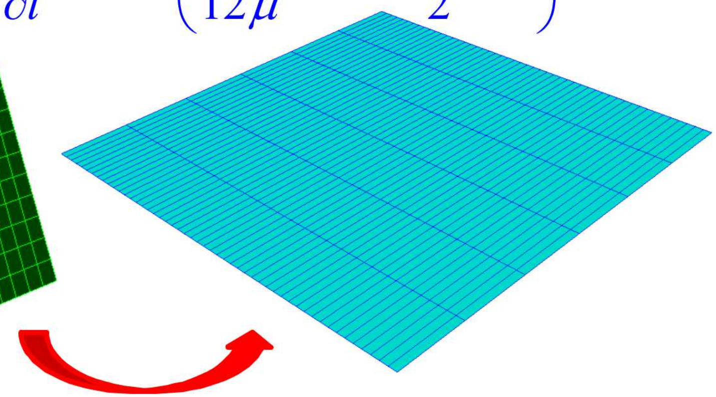
Blade – 3-D elasticity

$$\nabla \cdot \boldsymbol{\sigma}_s = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2}$$

$$\boldsymbol{\sigma}_s = G\left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right) + \lambda\left(\nabla \cdot \mathbf{u}\right)\mathbf{I}$$

Gap – Reynolds Lubrication

$$\frac{\partial h}{\partial t} = \nabla_{II} \cdot \left(\frac{h^3}{12\mu}\nabla_{II} p - \frac{h}{2}\mathbf{t}V_W\right)$$



Fluid structure interaction coupling

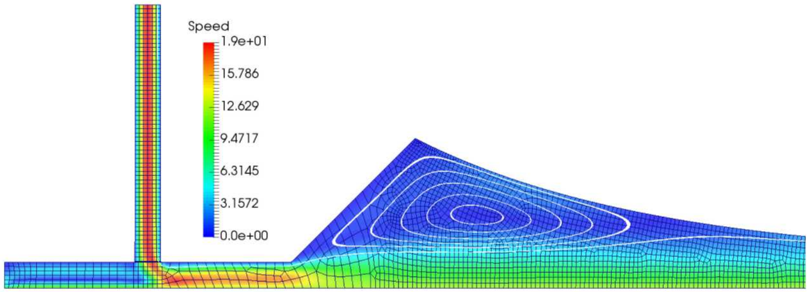
$$\mathbf{n} \cdot \boldsymbol{\sigma}_s = -\mathbf{n}p$$

$$h = h_0 - \mathbf{n} \cdot \mathbf{u}$$

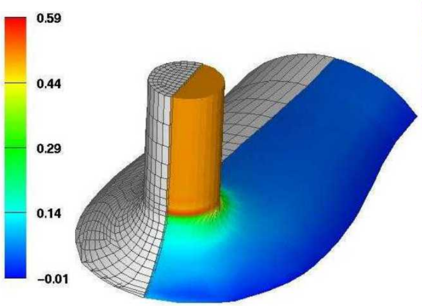
Solved with finite element method – Goma 6.0

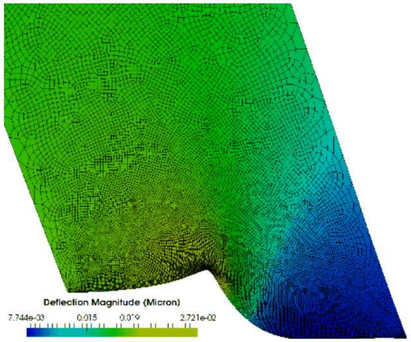
Simulation Tool: Goma 6.0

2014 R&D 100 Award Winner



- Multiphysics ***finite element*** code, suitable for both ***research*** and ***production***
- Fully-coupled ***free*** and moving ***boundary*** parameterization – ALE, Level Set, etc.
- Modular code; ***easy to add equations*** – currently has 180+ differential equations
- ***Open source***! Available at http://goma.github.io
- ***Goma 6.0. training*** is available!



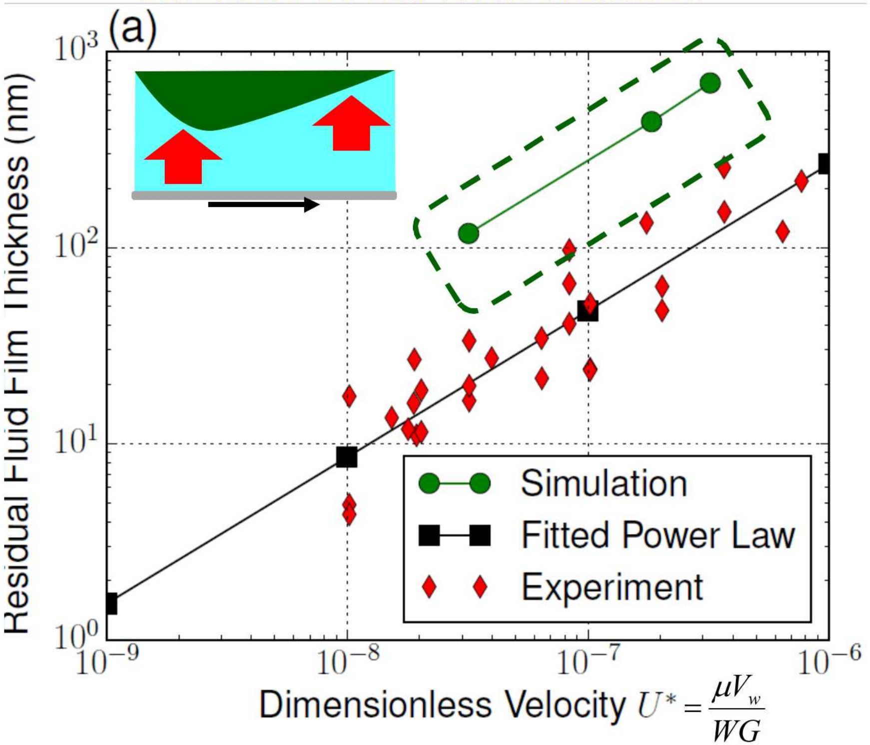


Goma has been used successfully in coating manufacturing for 3 decades!

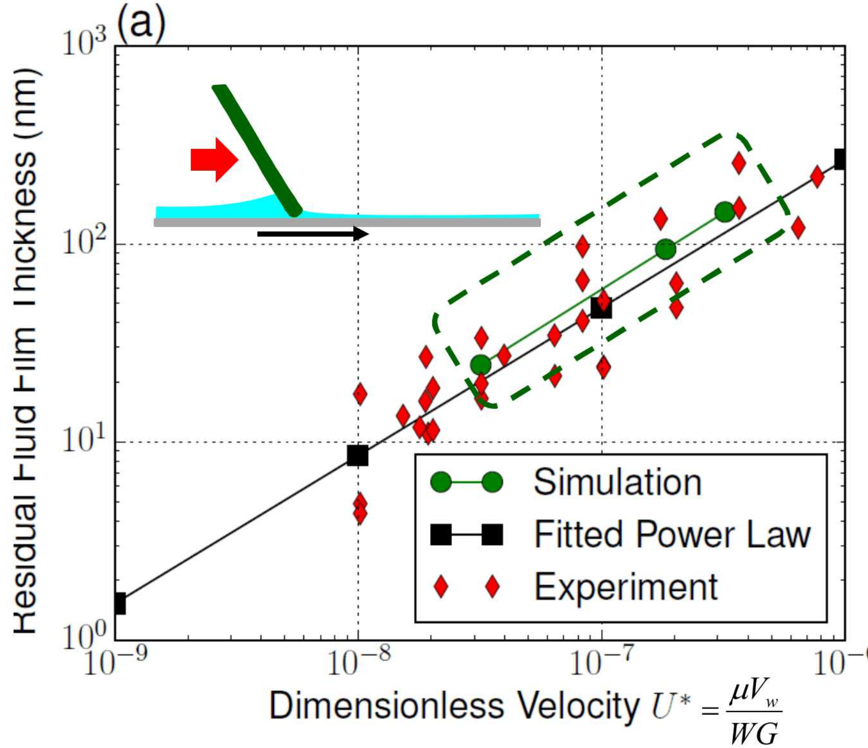
Model Validation

Hariprasad et al. (2016). *Journal of Applied Physics*, *119*(13), 135303.

Include local indentation



Include full structure

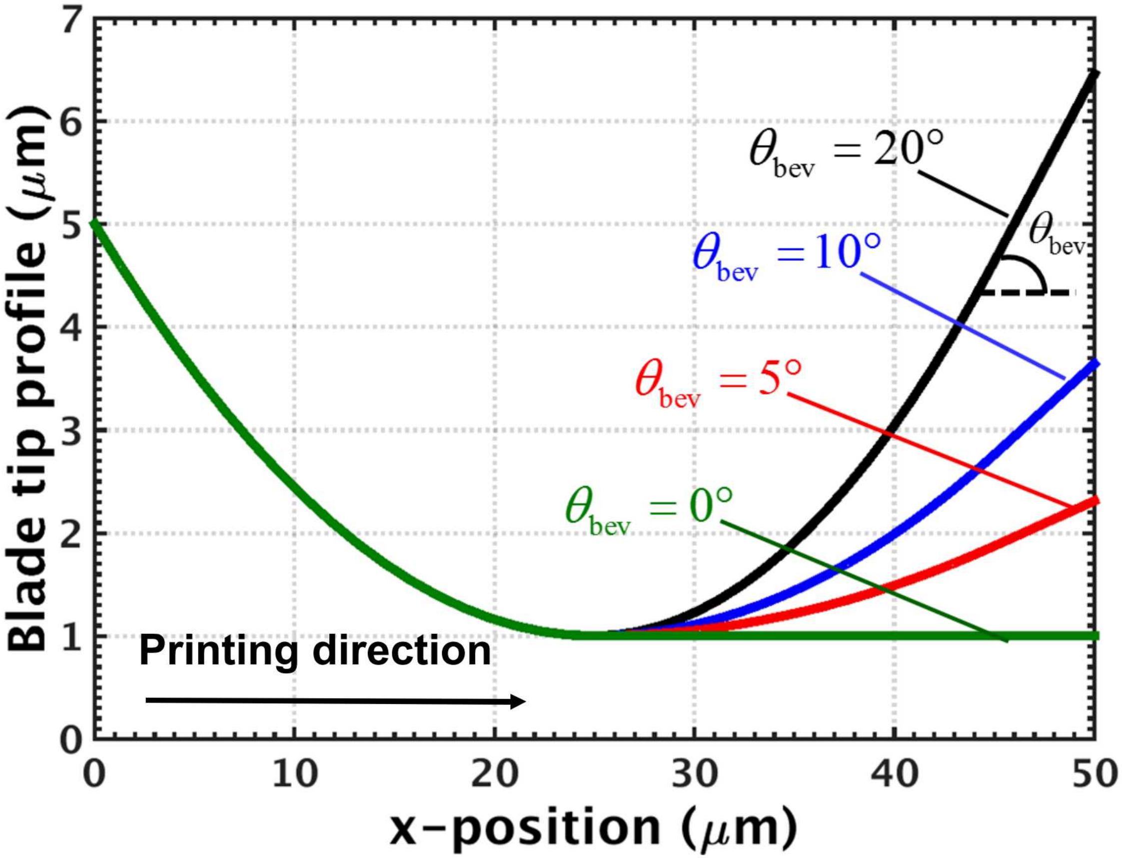


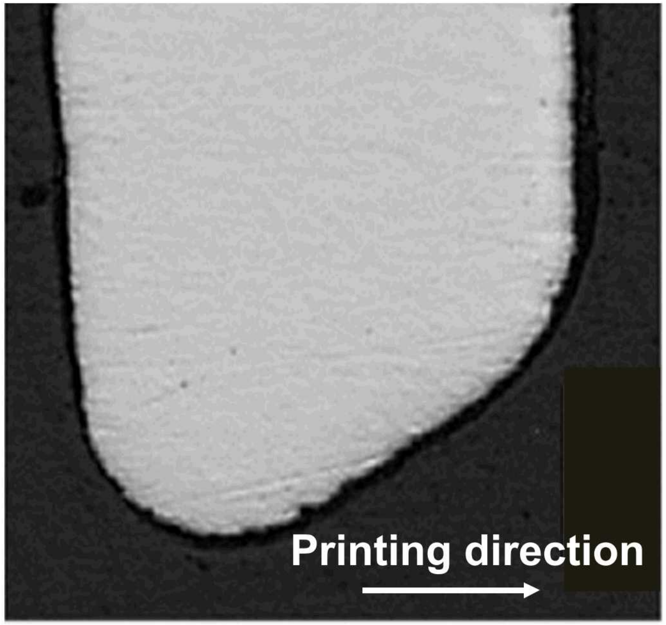
- Including ***local deformation of blade tip*** yields the ***correct trend*** and power law exponent but ***over-predict the film thickness***

- Including ***full structure mechanics***, i.e. bending of blade body, yields correct result – in doing that we discovered that film thickness is ***very sensitive to blade shapes***

Blade Shapes Parameterization

Tjiptowidjojo et al. (2018). *Journal of Coating Technology and Research*, *15*(5), 983-992.

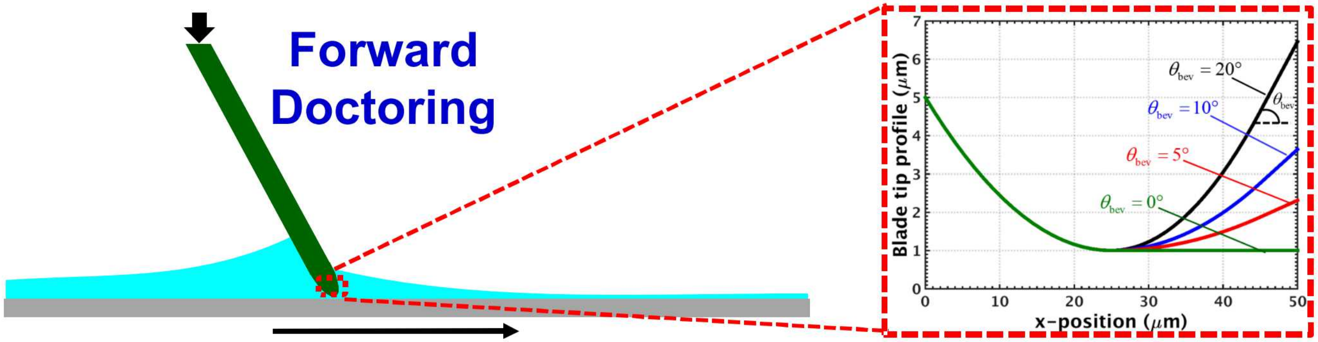


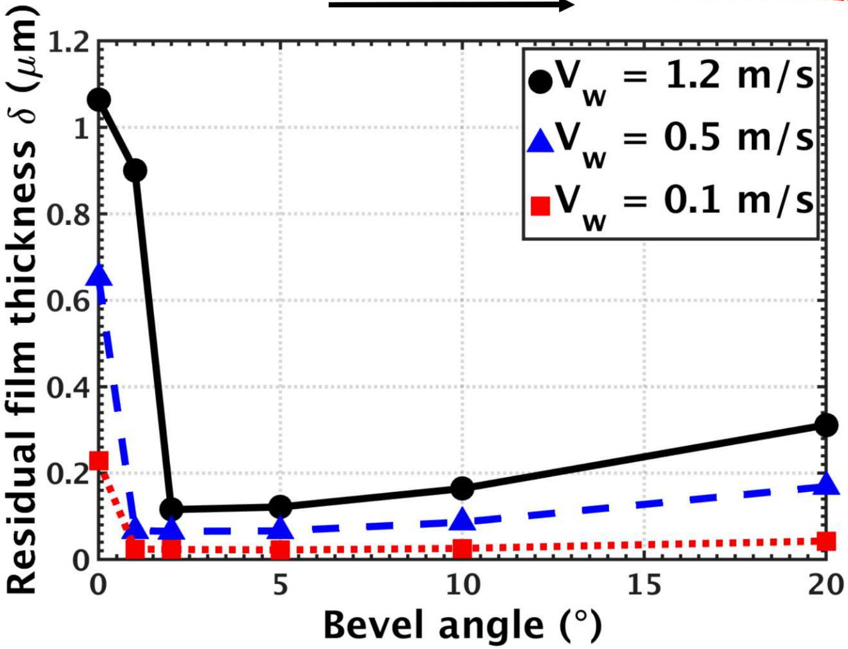


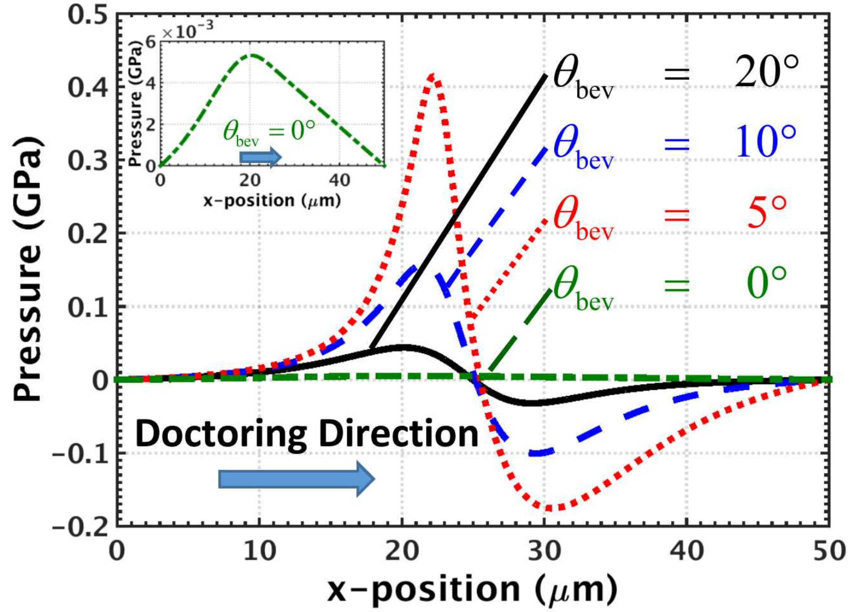
Optical micrograph of blade tip used in the experiments

- Approximate ***bevel shape*** of blade tip as segments of parabolas and line with ***specified take-off angle***
- Alter ***blade's sharpness*** by altering bevel angles

Effect of Speed

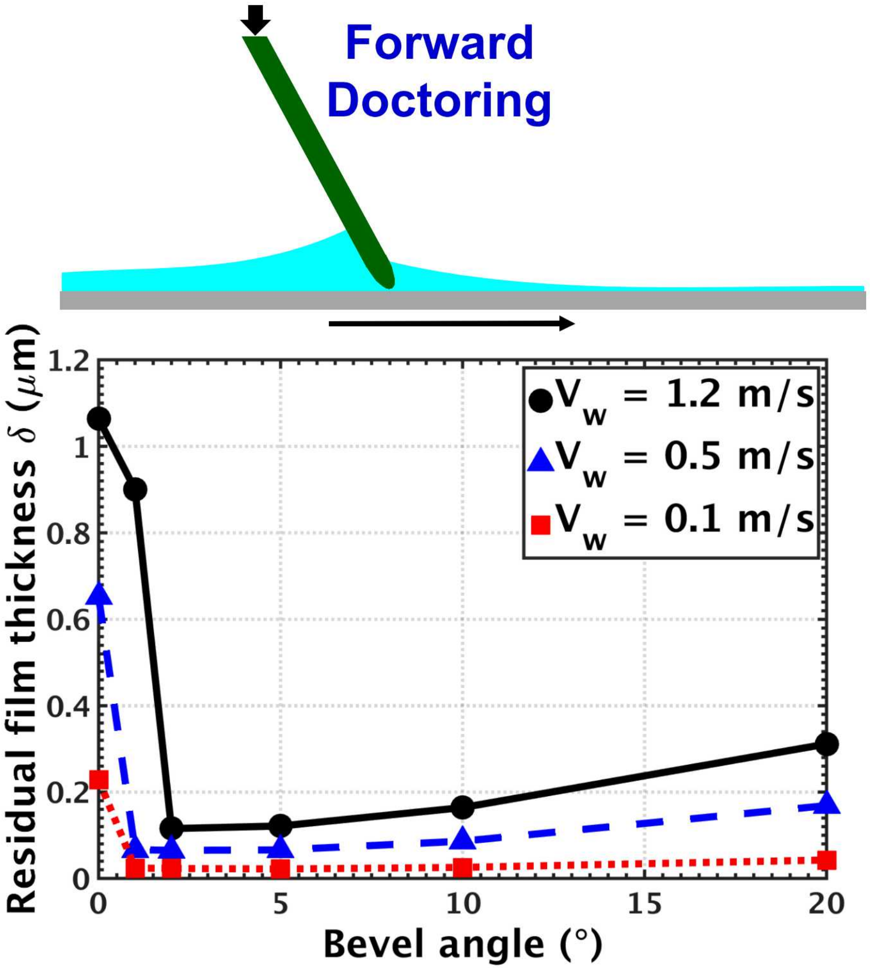


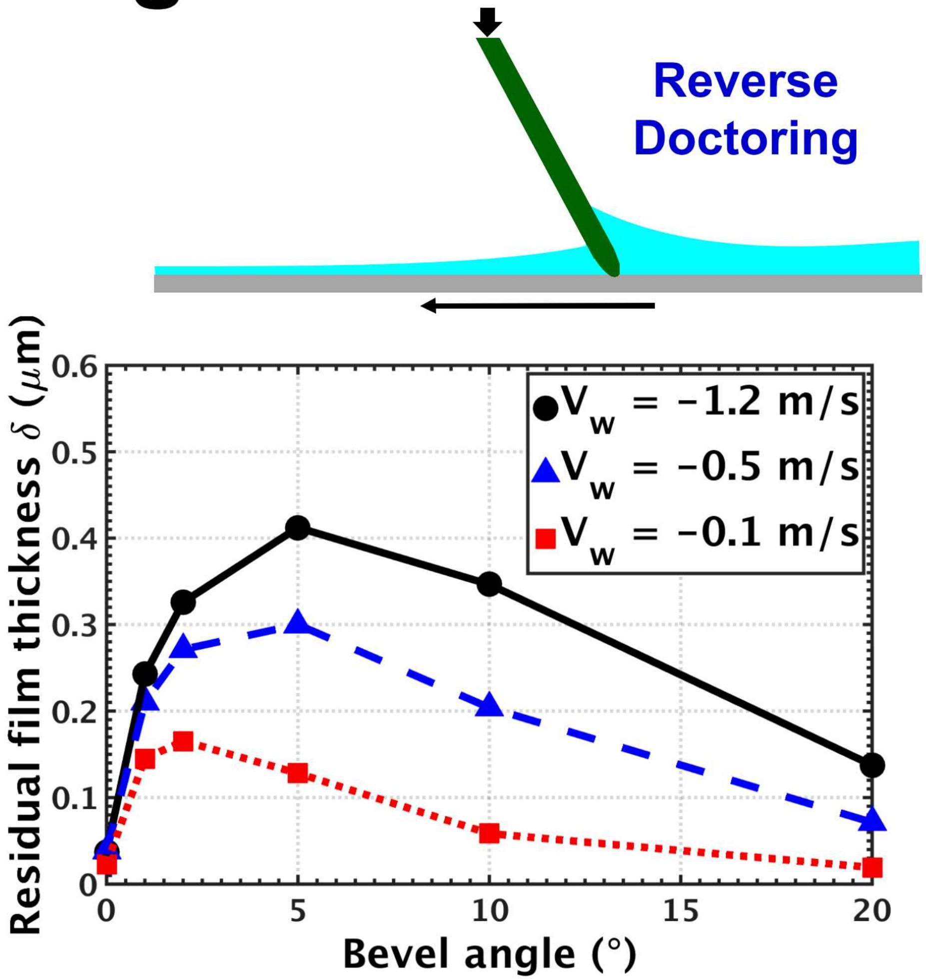




- Higher doctoring speed leads to thicker residual film – ***elastohydrodynamic regime***
- Blade shape ***dictates pressure field → residual film thickness***
- Shape effect lessens at lower speed ***→ lower lubrication pressure variation***

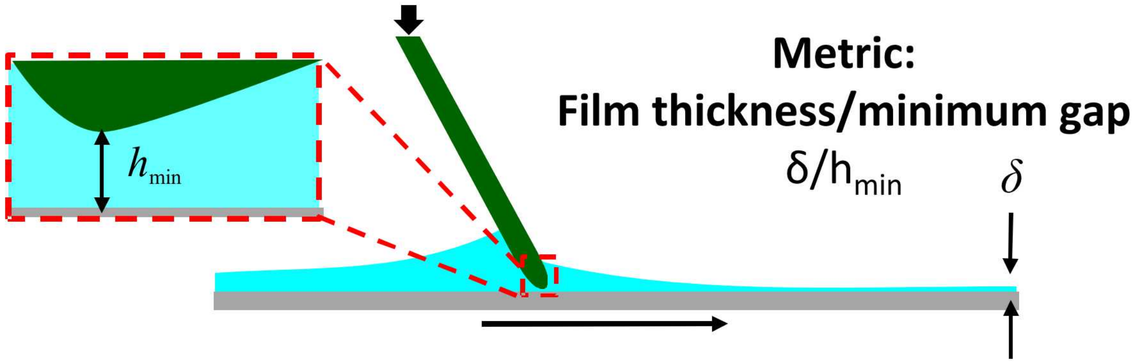
Effect of Doctoring Direction

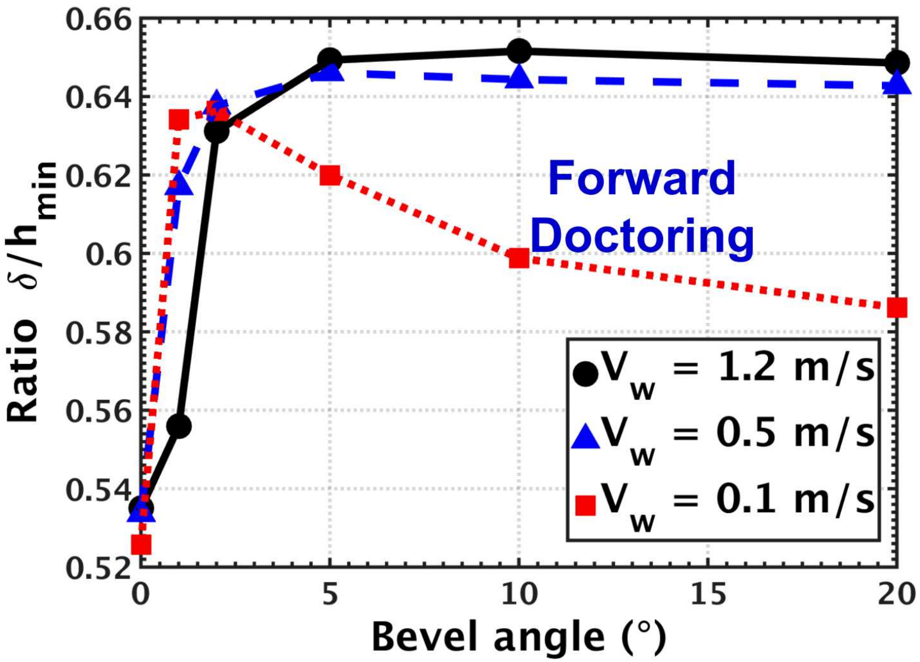


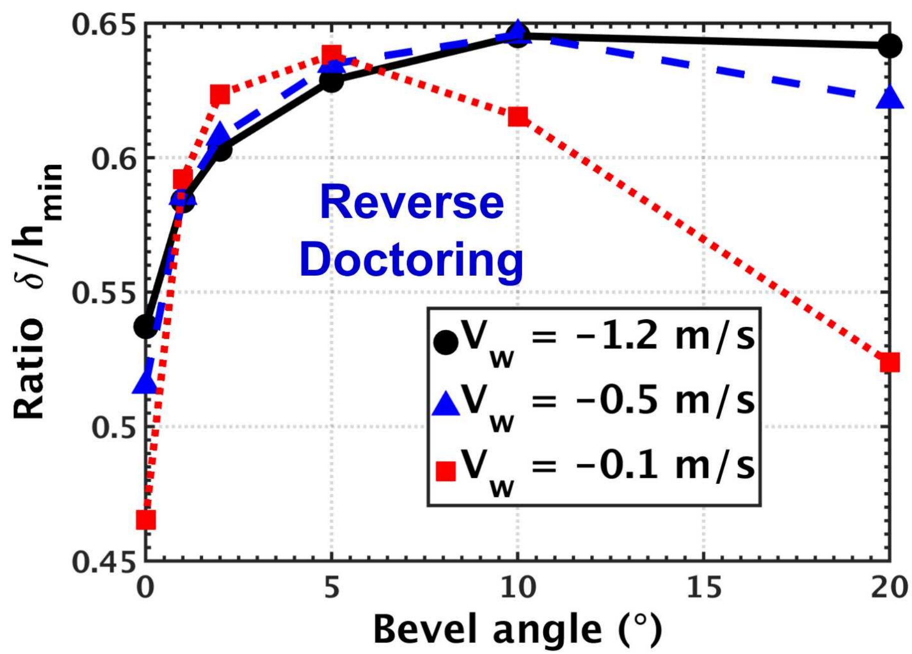


- Change of doctoring direction effectively ***changes blade shape*** → ***pressure field***
- Most dramatic changes occur in ***zero bevel angle***: Converging turns to diverging → ***thinner residual film***
- Will it ***accelerate blade wear-out?***

Predicting Blade Wear

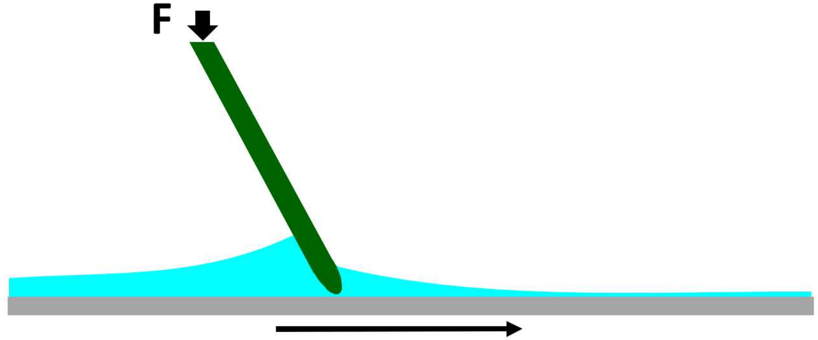


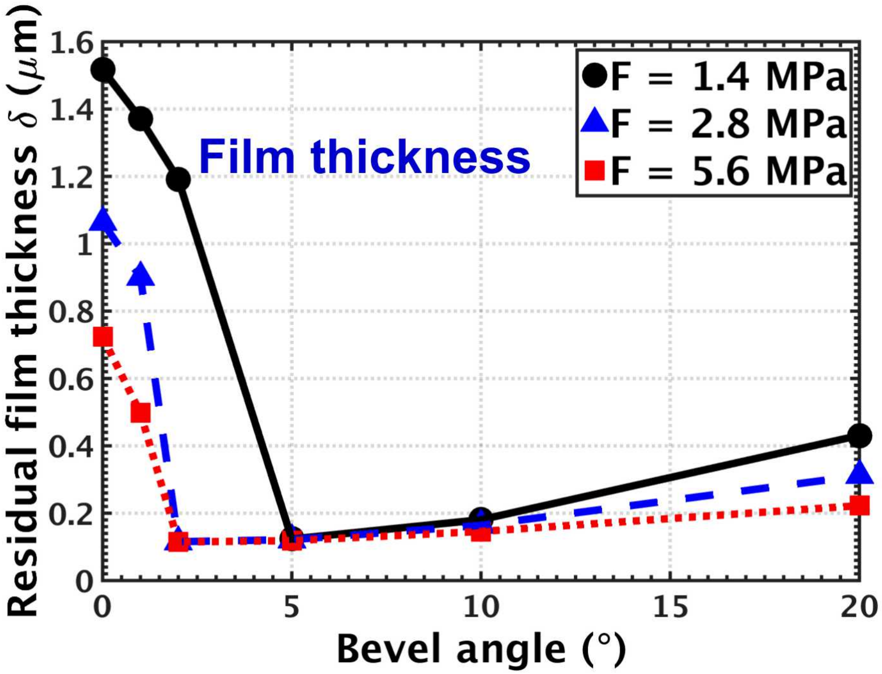


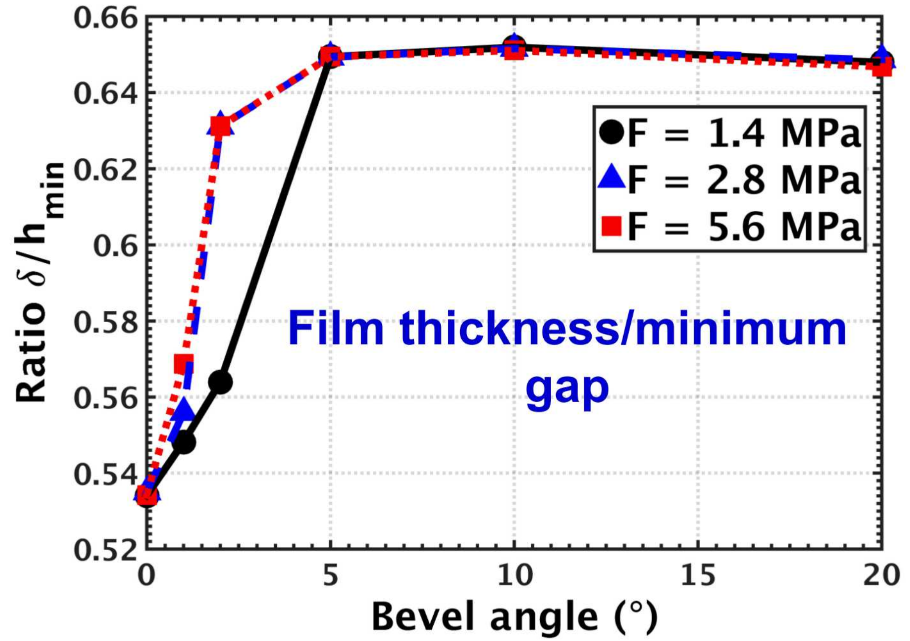


- Ratio is insensitive to doctoring direction
- Reverse doctoring at zero bevel angle gives ***thinnest film and least likely to blade wear***

Effect of Loading Force







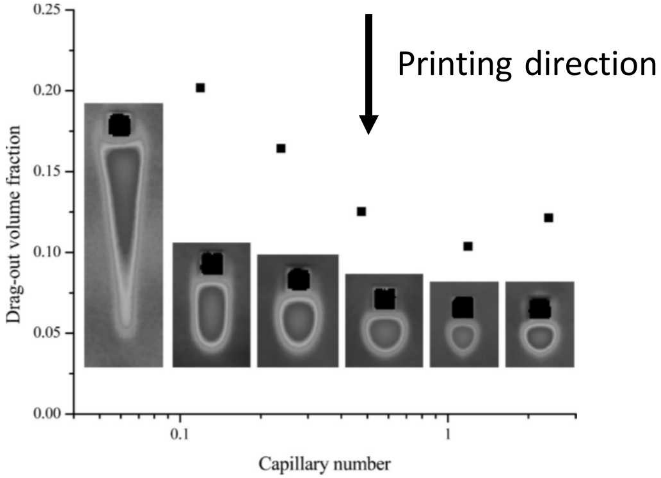
- Higher loading force results in thinner residual film → ***counteracting lubrication pressure***
- Does not lead to higher likelihood to blade wear

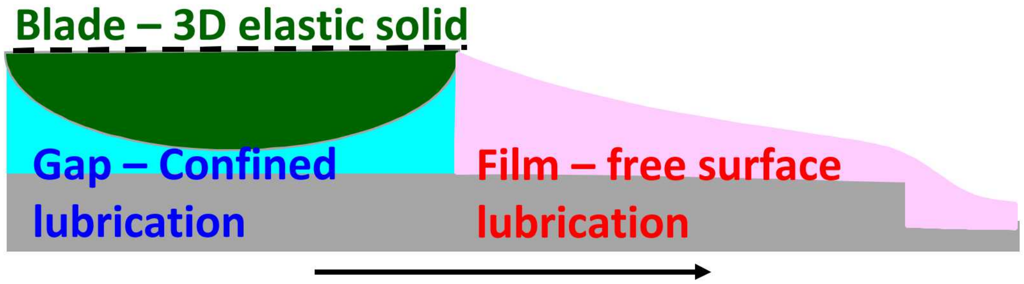
Summary

- Developed and validated computation model for doctor blade process in gravure printing
- Reverse doctoring leads to thinner film without added risk of blade wear

Future Works

- Address "drag out" in doctoring
- Include the effect of particles – colloidal ink systems





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4. Kitsomboonloha, R., Morris, S. J. S., Rong, X., & Subramanian, V. (2012). Femtoliter-scale patterning by high-speed, highly scaled inverse gravure printing. *Langmuir*, *28*(48), 16711-16723.

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