COATING TECH
SLOT DIES

PROCESS KNOWLEDGE · PRECISION · PERFORMANCE

THE EFFECTS OF VISCOELASTIC BEHAVIOR ON COATING

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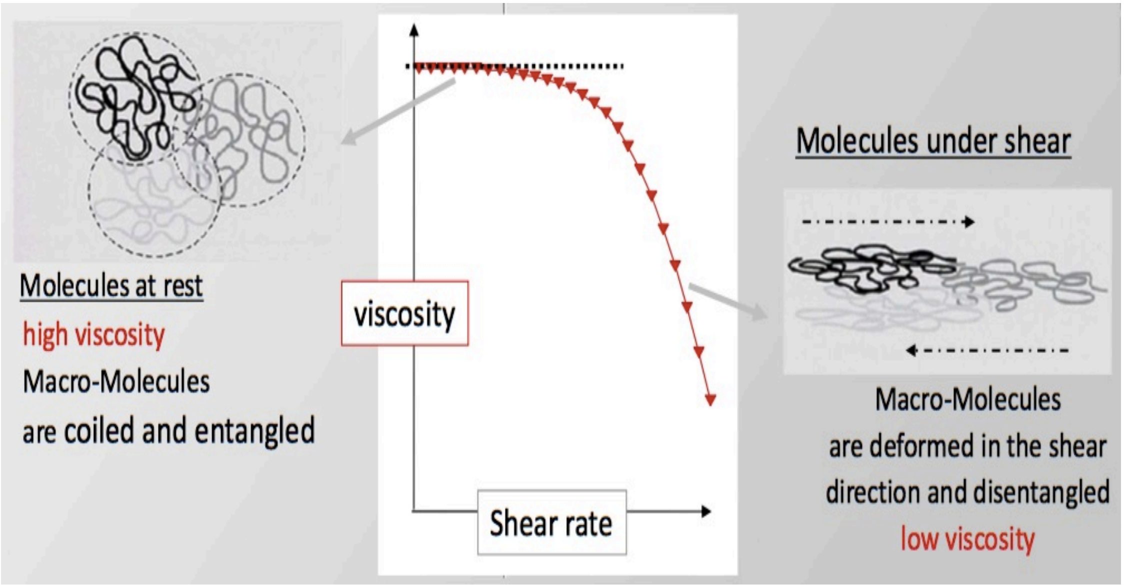
VISCOELASTICITY

- Viscosity (shear rate versus viscosity)
- Elasticity (stress and velocity interaction)



VISCOSITY

- (complex) Rheology = a curve, not a point
- Storage and Loss Modulus (G' & G") = spring constant (PE & KE)
- Molecular Weight (distribution)

Shear stress

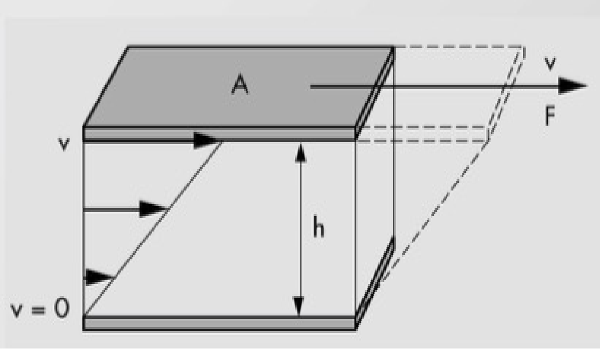
$$\tau = \frac{F}{A} = \frac{\text{shear (force)}}{\text{(shear) area}} = \frac{\text{N}}{\text{m}^2} = Pa$$

Shear rate

$$\dot{\gamma} = \frac{v}{h} = \frac{\text{velocity}}{\text{gap}} = \frac{\text{m/s}}{\text{m}} = \frac{1}{s}$$

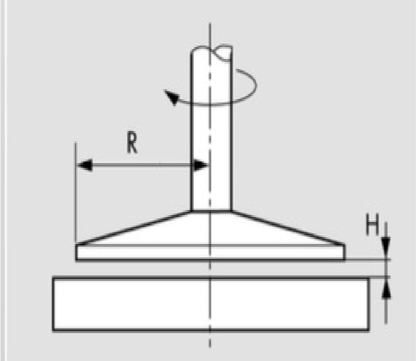
Viscosity

$$\eta = \tau \div \dot{\gamma}$$



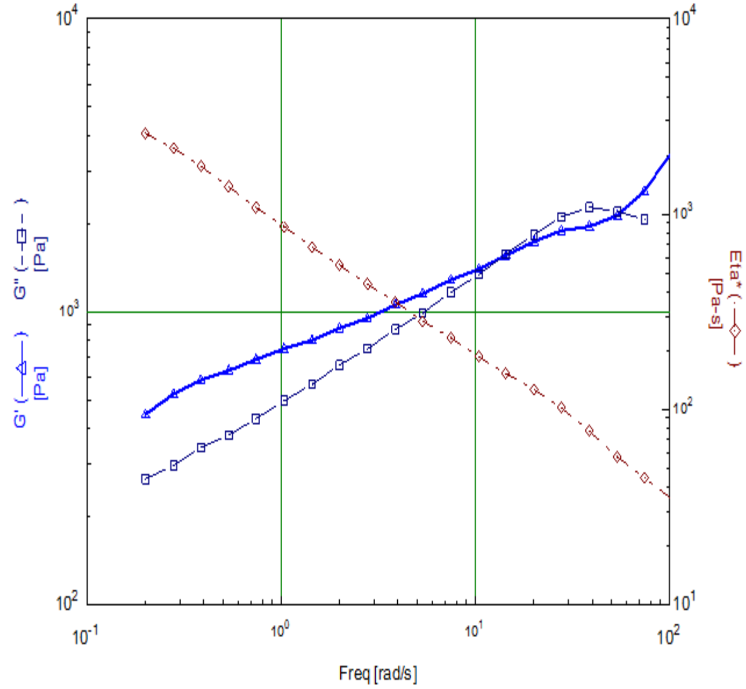
VISCOSITY

- (MORE complex) Rheology = hysteresis
- Stress-relaxation
  - Snap back (lack of self-leveling)
  - Expansions and Contractions (manifold design)
- Film split



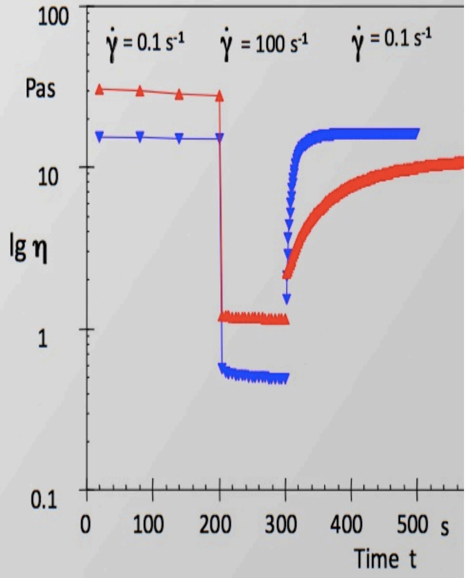
VISCOSITY

- tan δ = G"/G' (balance of viscoelastic behavior)



ELASTICITY

- No modulus dependence on time
- Elongational testing (rough or elegant)



RHEOLOGY & COATING

• Reynolds	$Re = \rho VL/\mu$	(inertial forces) / (net viscous force)
• Capillary	$Ca = \mu V/\sigma$	(viscosity induced pressure gradient) / (capillary pressure)
• Stokes	$St = \rho gL^2/\mu V$	(gravity force) / (net viscous force)
• Elasticity	$El = \mu V/EL$	(viscous stress) / (elastic stress in boundary)
• Deborah	$De = \lambda V/L$	(elastic stress within liquid) / (viscous stress)

COATING

- Recognized phenomenon
- Defect analysis
- Crossroads of liquid coating and polymer extrusion

COATING

- Viscoelasticity dominates, then time dependent stress

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_0}$$

$E_r(t) =$ *stress relaxation modulus*

$\sigma(t) =$ *stress*

$\varepsilon_0 =$ *applied strain*

- Time is greater at lower temperatures

COATING

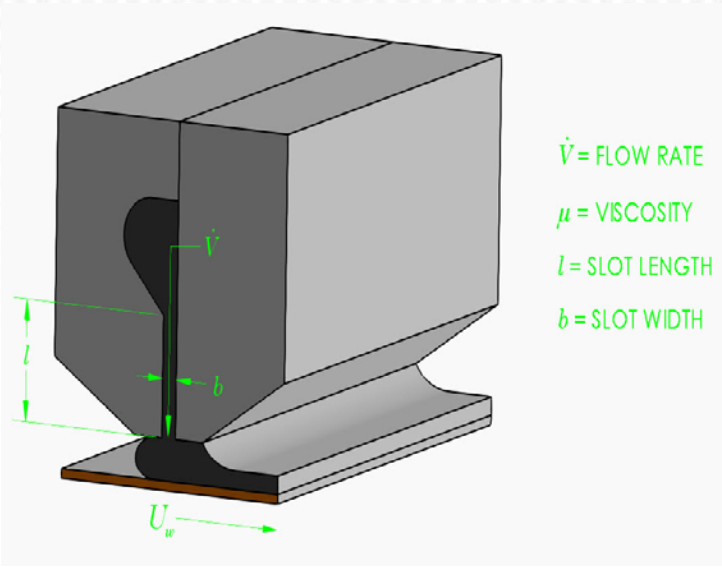
- Film split
  - Misting
  - Roll spatter (high MW = more splatter)

$$\frac{\Delta P}{\Delta X} = 12\mu\left(\frac{\frac{(U_1 + U_2)}{2}}{H^2} - \frac{Q}{H^3}\right)$$

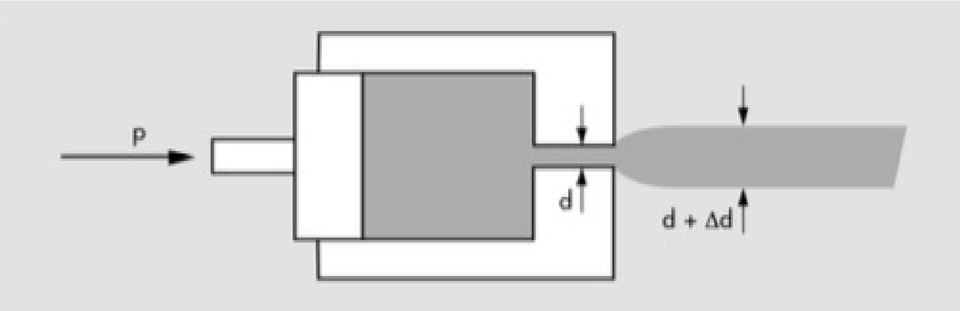
P = pressure
X = distance
μ = viscosity
U_1 & U_2 = roll speeds
Q = volumetric flow rate
H = separation between roll surfaces

COATING

- Pre-metered flow control
  - Forced flow (no self-leveling)
  - Die swell (edge bead)
  - Neck-in (speed effects)
  - Retraction (wrinkling, curl or voids)



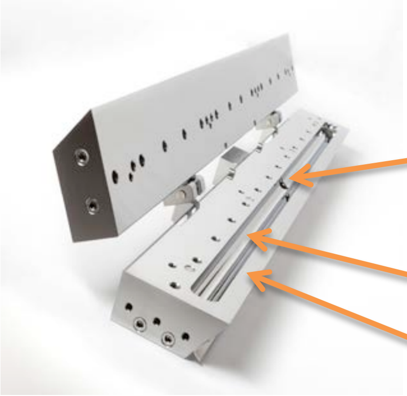
$$\dot{V} = \frac{\Delta p b^3}{12 \mu L}$$



COATING

- Pre-metered flow control

$$\dot{V} = \frac{\Delta p b^3}{12 \mu L}$$



COATING

- 2D non-Newtonian flow models (internal flow)
  - Casson (short time model) $\sqrt{\tau_{xy}} = \sqrt{\tau_0} + \sqrt{\eta}\sqrt{\gamma_{xy}}$

$\tau_{xy} = shear\ stress$

$\tau_0 = apparent\ yield\ stress$

$\eta = viscosity$

$\gamma_{xy} = rate\ of\ strain$

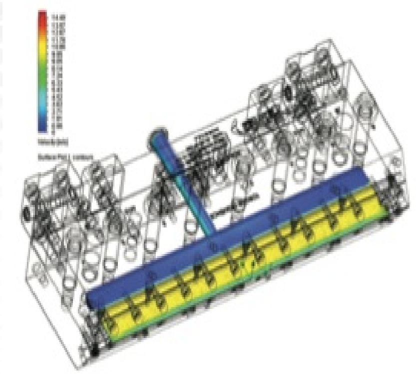
  - Maxwell (long time model)

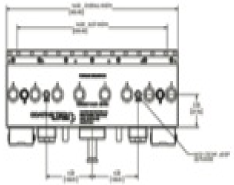
$$\tau_{xy} + \frac{\eta}{G}\frac{d\tau_{xy}}{dt} = -\eta\gamma_{xy}$$

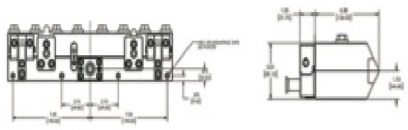
$G = elastic\ shear\ modulus$

COATING

- 3D Finite Element Analysis (defined boundary conditions)
  - Stress Relaxation
  - Time-Temperature and Boltzmann Superposition principles
  - Creep (long time frames)

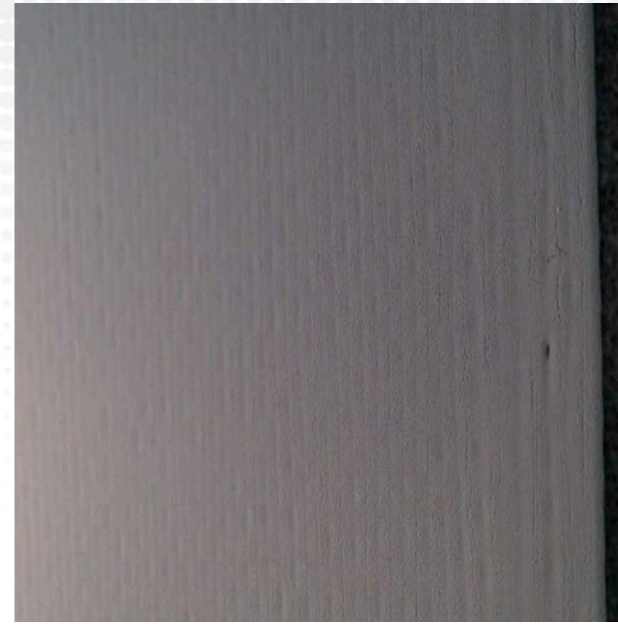


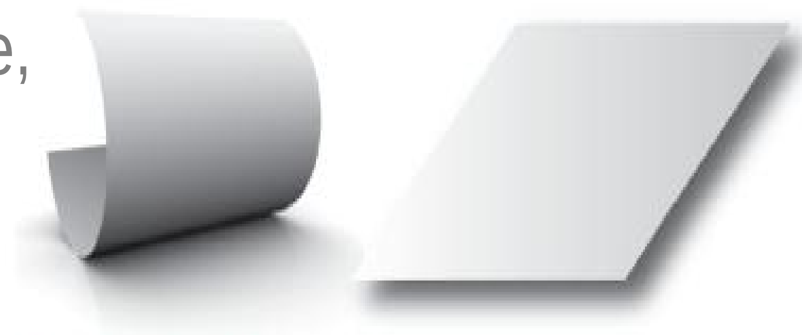




COATING

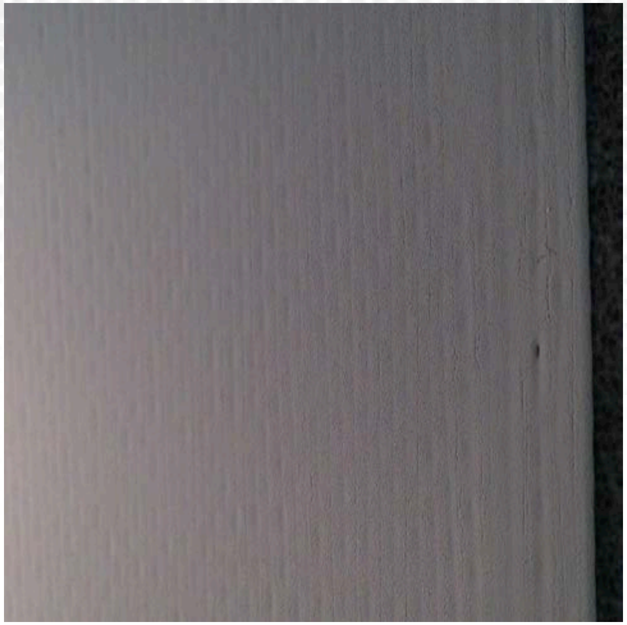
- Defects
  - Coating while stressed (ribbing, neck-in and edge bead/die swell)
  - Curing while stressed (wrinkle, curl and voids)





COATING

- Solutions
  - Ribbing = positional adjustment
  - Edge bead = slot to substrate gap
  - Neck-in = speed related
  - Wrinkle/Curl = reduce stress at coating or during curing
  - Voids = limit of process



SUMMARY

- Viscoelasticy is complex – test appropriately
- Reduce stress to improve coating
- Implement mathematical understanding to coating process development
- Coating window is fundamentally reduced because of viscoelastic behavior

The science of slot dies