Gravure Roll Coating

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There are practical challenges that arise during the coating process:

- Ribbing
- Scratching the web
- Solid build up

Important parameters include:

- Speed ratio \((U_{\text{web}}/U_{\text{roll}})\)
- Gravure cell geometry
- Web loading
- Fluid properties

Offset versus Direct

Offset gravure
- Deformable roll
- Web
- Doctor Blade
- Gravure roll

Direct Gravure
- Web
- Gravure roll
- Doctor Blade

Can involve subsequent transfer nips

Focus of this presentation
Can observe eddies upstream and downstream of web – roll contact- similar to reverse mode smooth roll coating.

Streaking observed at speed ratios greater than around 1.2.

- The upstream meniscus enters the groove completely and moves all the way to the downstream meniscus.
- Forms a tube from upstream to downstream - corresponds to a streak.

Stable bead

Streaking bead
Experimental Apparatus
Typical Results

(a) Film thickness $\mu$m

(b) Fractional pickout

Speed ratio

Graphs showing the relationship between speed ratio and film thickness/fractional pickout for different laser engraved and quadrangular patterns.
From a modelling perspective what is really of interest is the coating bead and less what is going on at cell level. In this frame of reference we know that:

1. Fluid is entering the coating bead from the gravure cells
2. Fluid leaves either on the web or in the cells
3. There is a relation between the web tension, the bead pressure and the overall curvature of the web.
In the case of a smooth roller the flow throughout the coating bead can be described very well by lubrication theory.

\[ q_x = a(g) \frac{dp}{dx} + Sb(g) + c(g) \]

<table>
<thead>
<tr>
<th>dp/dx</th>
<th>Pressure gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Speeds Ratio (web-to-roll)</td>
</tr>
<tr>
<td>q_x</td>
<td>Volumetric flow-rate</td>
</tr>
<tr>
<td>a, b, c</td>
<td>Constants for a given gap (g)</td>
</tr>
<tr>
<td>h</td>
<td>Film thickness</td>
</tr>
</tbody>
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In the case of a smooth roller the flow throughout the coating bead can be described very well by lubrication theory. The flow rate is given by:

\[ q_x = a(g) \frac{dp}{dx} + Sb(g) + c(g) \]

The constants are a function of only gap (comes from the linearity of Stokes flow) and using lubrication theory they are:

\[ a = -\frac{h^3}{12\mu}, \quad b = \frac{h \times U_{\text{roll}}}{2}, \quad c = \frac{h \times U_{\text{web}}}{2} \]

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</tr>
<tr>
<td>(\mu)</td>
<td>Viscosity</td>
</tr>
</tbody>
</table>
Smooth roll models – a prelude to gravure coating

1) \[ \frac{dp}{dx} = \frac{q_x - Sb(g) - c(g)}{a(g)} \]

The large scale is governed by a series of differential equations which are solved as a boundary value problem in MATLAB.

Equations 1-3 describe the physics of the coating bead.

2) \[ \frac{dq}{dx} = 0 \]

Note: We also use an ad hoc moving mesh which adds a further equation

3) \[ \frac{d^2 h}{dx^2} = \frac{p}{t} \times \left(1 + \left(\frac{dh}{dx}\right)^2\right)^{\frac{3}{2}} \]
Equation 1 is solved to find the pressure along the coating bead.

1) \[
\frac{dp}{dx} = \frac{q_x - Sb(g) - c(g)}{a(g)}
\]

2) \[
\frac{dq}{dx} = 0
\]

3) \[
\frac{d^2h}{dx^2} = \frac{p}{t} \times \left( 1 + \left( \frac{dh}{dx} \right)^2 \right)^{3/2}
\]

<table>
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<td>S</td>
<td>Speeds Ratio (web-to-roll)</td>
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<tr>
<td>q_x</td>
<td>Volumetric flow-rate</td>
</tr>
<tr>
<td>g</td>
<td>gap</td>
</tr>
</tbody>
</table>
Equation 2 is required to maintain conservation of volume, and as the flow is assumed incompressible mass is also conserved.

Flow into the bead is delivered via the gravure cells and in this the case of reverse gravure roll coating it is negative.

\[
\frac{dp}{dx} = \frac{q_x - Sb(g) - c(g)}{a(g)}
\]

\[
\frac{dq}{dx} = 0
\]

\[
\frac{d^2 h}{dx^2} = \frac{p}{t} \left( 1 + \left( \frac{dh}{dx} \right)^2 \right)^{3/2}
\]
Equation 3 is a second order differential which defines the gradient and location of the web.

\[ \frac{dp}{dx} = \frac{q_x - Sb(g) - c(g)}{a(g)} \]

1) \[ \frac{dq}{dx} = 0 \]

2) \[ \frac{d^2h}{dx^2} = \frac{p}{t} \left( 1 + \left( \frac{dh}{dx} \right)^2 \right)^{3/2} \]

Smooth roll results – web shape

<table>
<thead>
<tr>
<th>h</th>
<th>Web location as measured from the top of the roller</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>Web tension</td>
</tr>
</tbody>
</table>

![Graph of web gradient and location vs. non-dimensional bead length](image)
Gradient of web entering and leaving

\[ \frac{dh}{dx_{us}} = -\beta \quad ; \quad \frac{dh}{dx_{ds}} = 0 \]

Relationship between film thickness and radius of curvature (Bretherton, 1960).

\[ \frac{h}{r} = 1.34\left(\frac{\mu U}{\sigma}\right)^{2/3} \]

Allows conditions on pressure at interface to be derived

<table>
<thead>
<tr>
<th>( x_{us} )</th>
<th>Up-stream location</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{ds} )</td>
<td>Down-stream location</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Wrap angle</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Viscosity</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Surface tension</td>
</tr>
<tr>
<td>( b )</td>
<td>Film thickness</td>
</tr>
<tr>
<td>( r )</td>
<td>Radius of meniscus curvature</td>
</tr>
<tr>
<td>( U )</td>
<td>Local velocity</td>
</tr>
<tr>
<td>( h )</td>
<td>Film thickness</td>
</tr>
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</table>
In actuality we do not have a smooth roll because of the topography of the cells. We need to account for:

- Different length scales of the cells and coating bead
- Sharply changing topography
- Flow within the cells (i.e. Re-circulations)
We need to adapt the lubrication equation to account for the surface topography. This done by numerically calculating the constants $a$, $b$ and $c$. (Hewson et al, 2011)

$$q_x = a(g) \frac{dp}{dx} + Sb(g) + c(g)$$

$$a = -\frac{h^3}{12\mu}, \quad b = \frac{h \times U_{roll}}{2}, \quad c = \frac{h \times U_{web}}{2}$$

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$dp/dx$</td>
<td>Pressure gradient</td>
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<td>$a$, $b$, $c$</td>
<td>Constants for a given gap $(g)$</td>
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<tr>
<td>$\mu$</td>
<td>Viscosity</td>
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The CFD package COMSOL Multiphysics is used to numerically solve for \( a \) and \( b \), while \( c \) is equal to the volume the domain (see picture).

The flow domain is solved over a range of gaps such that entire coating bead can be represented.

\[
q_x = a(g) \frac{dp}{dx} + Sb(g) + c(g)
\]

<table>
<thead>
<tr>
<th>Condition</th>
<th>( \frac{dp}{dx} )</th>
<th>( S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
1. Create the constants a, b, c for the look up table.

2. From here the large scale can now be solved as before, but with the need to interpolate to find the correct constant for the current gap.

\[
\frac{dp}{dx} = \frac{q_x - Sb(g) - c(g)}{a(g)}
\]

2) \( \frac{dq}{dx} = 0 \)

3) \( \frac{d^2h}{dx^2} = \frac{p}{t} \times \left(1 + \left(\frac{dh}{dx}\right)^2\right)^{3/2} \)
For initial validation a model was produced to replicate results found in an earlier paper. An example of which is shown here.

A typical cell was created in COMSOL Multiphysics (seen right). This cell geometrically is a good approximation but ignores:

- Cell to cell variations
- Surface roughness
- Cell non-symmetry

Varying speed ratio has a clear impact on the resulting film thickness, and similar trends can be seen in existing work (Kapur 2003).
1. Adapting lubrication to suit a discrete gravure roller
   - Multi-scale method
   - Solved the small scale using CFD (COMSOL)
   - Used the small scale to inform the large scale
   - The large scale definitions remained the same

2. The method can then be extended to account for the different geometry found on various discrete gravure rolls.

Ongoing work includes:
   - More thorough validation
   - Establish meta-model