Wrinkling of Foils

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Questions

- Will foils run wrinkle-free on equipment designed for paper and film handling?
- Are foils more sensitive than films to specific wrinkle causes?
- What best practices will allow running thin, wide foils without wrinkles?
## Aluminum Foil vs. Polyester Film

<table>
<thead>
<tr>
<th>Property</th>
<th>Aluminum Foil</th>
<th>Polyester Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus of copper and aluminum</td>
<td>69 GPa (temp. ind.)</td>
<td>3.4-4.8 GPa (temp. dep.)</td>
</tr>
<tr>
<td>+ Higher modulus increase stiffness and resistance to buckling – wrinkling.</td>
<td></td>
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<tr>
<td>- Higher modulus increases stress variations created by roller misalignment</td>
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<td></td>
</tr>
<tr>
<td>Yield Stress</td>
<td>140 MPa</td>
<td>140-280 MPa (0.92-0.48 mil)</td>
</tr>
<tr>
<td>Yield Strain</td>
<td>0.2%</td>
<td>4-5%</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>2.7e-5 in/in/C</td>
<td>2e-5 in/in/C</td>
</tr>
<tr>
<td>Density</td>
<td>2.8 g/cc</td>
<td>1.4 g/cc</td>
</tr>
<tr>
<td>Tear Resistance</td>
<td>Low</td>
<td>Modest-high</td>
</tr>
</tbody>
</table>
Aluminum Foil vs. Polyester Film

- Elastic modulus of copper and aluminum is 10-20x higher than polyester.
  - Higher modulus increase stiffness and resistance to buckling – wrinkling.
  - Higher modulus increases stress variations created by roller misalignment

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<tr>
<th>Property</th>
<th>Aluminum Foil</th>
<th>Polyester Film</th>
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<tbody>
<tr>
<td>Elastic modulus</td>
<td>10 Mpsi (temp. ind.)</td>
<td>0.5-0.7 Mpsi (temp. dep.)</td>
</tr>
<tr>
<td>Yield Stress</td>
<td>21 kpsi (0.92-0.48 mil)</td>
<td>21-41 kpsi</td>
</tr>
<tr>
<td>Yield Strain</td>
<td>0.2%</td>
<td>4-5%</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>13e-6 in/in/F</td>
<td>9e-6 in/in/F</td>
</tr>
<tr>
<td>Density</td>
<td>0.0975 lb/in^3</td>
<td>0.047 lb/in^3</td>
</tr>
<tr>
<td>Tear Resistance</td>
<td>Low</td>
<td>Modest-high</td>
</tr>
</tbody>
</table>

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Detail on typical strain

For a typical tension of 175 N/m per 25 microns (6.9 MPa)* the strain of aluminum and polyester will be:

- Strain (Al) = 0.0001 = 0.01%
- Strain (PET) = 0.002 = 0.2%

Conclusion: Typical strains of Al foils are 20X lower than PET.

* 1 PLI per mil (1000 psi)
Roller misalignment is a well understood wrinkle mechanism, typically documented in tension-roller angle contour plot plots.
This shear wrinkle plot shows how wider polyester films are more wrinkle sensitive.
Shear Wrinkles – Aluminum vs. Polyester as a Function of Tension

This shear wrinkle plot shows how thickness has a more dramatic effect on wrinkle-free foil handling for a given width.

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Shear Wrinkles vs. Foil Width

Models predict that foils are especially sensitive to misalignment at greater widths.

Wide foils look like a web handling nightmare.
Shear Wrinkling Experimental Setup

Shear wrinkle models are confirmed with controlled wrinkling experiments.

Foil is handled through a known web path and made to wrinkle from an intentionally misaligned roller, monitoring wrinkle formation as a function of tension, roller misalignment, and other variables.
Shear Wrinkle Experimental Setup

Pivoting Plane

Tramming Plane
Shear Wrinkling in Wide Al and Cu Foils – Results vs. Theory

At 40 & 80 N/m, Al would NOT wrinkle.

Al: 20 micron, 1.2m
Cu: 12 micron, 1.2m
Shear Wrinkling in Copper Foil – Results vs. Theory

Regime I-II Transition Zone

h = 10 micron, w = 0.4m

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3 Rollers, 3 Wrinkles, 3 Mechanisms

1. Classic shear wrinkles from misaligned roller.
2. Backside wrinkle forming on roller upstream of misaligned roller due to moment transfer.
3. Gathering wrinkle from roller deflection.
Shear Wrinkling Experimental Observations

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Classic shear wrinkles from misaligned roller.

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Backside wrinkling forming on roller upstream of misaligned roller due to moment transfer.
Slack Edge Condition

There will be a slack edge here if: $\theta w > L \varepsilon$

$\theta$ = angle of misalignment (radians)

$w$ = width (in.)

$L$ = span length (in.)

$\varepsilon$ = average strain (dimensionless)
Moment Transfer

No moment transfer

Moment transfer + parallel entry

Moment transfer + No parallel entry
Moment transfer and $L_2 > L_1$ can lead to negative steering.

**Case 1:** High Traction on UR (all bending in $L_1$-span)

**Case 2:** Moment Transfer on UR (negative steering in $L_2$-span)

**Case 3:** Low Traction on UR (effective steering span increases)
Case 2: Moment Transfer on UR (negative steering in L₂-span)
Shear Wrinkling Experimental Observations

- Stationary Downstream Wrinkle

Gathering wrinkle from roller deflection.

Tramming Plane

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Detail on slack edge, highly likely moment transfer

- Slack edges begin when angle of misalignment $\times$ web width is greater than span length $\times$ strain. \[ \theta w > L \varepsilon \]
- For any web span with a $L/W = 1$, the critical misalignment is equal to the strain.
- Critical angle for aluminum = 0.0001 = 0.1mm/m
- Critical angle for polyester = 0.002 = 2mm/m

Conclusion: Slack edges and moment transfer are 20x more likely with aluminum than polyester webs.
Details on strain to buckle in span

- The critical stress to buckle a tensioned web in a span (troughing), the precursor to buckled web passing over a roller (wrinkling):

\[
\sigma_{ycrit} = -1.73 \left( \frac{h}{L} \right) \sqrt{\sigma_x E_{iso}}
\]

\[
\varepsilon_{ycrit} = \frac{\sigma_{ycrit}}{E_x} = -1.73 \left( \frac{h}{L} \right) \sqrt{\frac{\sigma_x}{E_x}} = -1.73 \left( \frac{h}{L} \right) \sqrt{\varepsilon_x}
\]

- Comparing aluminum foil to polyester at the same tensioning stress, the critical buckling strain will be proportional to the square root elastic strain.

Conclusion: With Al strains typically 20x lower than PET strains, critical buckling strain for aluminum will be 4.5x lower than PET.
Lateral Strains Induced by Deflection

\[ \varepsilon \]

\[ \varepsilon_d \]  
On-Roller TD Strain

\[ \varepsilon_s \]  
Pre-Roller TD Strain

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Details on strain from roller deflection

Roller deflection ‘gathering’ wrinkles are a complicated relationship of roller and web parameters.

- In-span buckling criteria is \( f(\varepsilon^{0.5}) \)
- On-roller buckling criteria of the web \( f(t/R) \)
- Deflection of roller \( f(1/R^4, w_{\text{roller}}) \), plus web tension magnitude, wrap angle and orientation.
Details on strain from roller deflection

- Maximum compressive strain has two components:
  1) Gathering in the upstream span and
  2) Gathering while in contact with the roller.

- The compressive strain has to be delivered by traction between the web and roller, increasing with width, coefficient of friction, and many lubrication factors.
Details on strain from roller deflection

Conclusion: Predicting wrinkles from roller deflection is difficult, but experience shows thin foils are much more sensitive to this mechanism than polyester films.
Details on strain and temperature variations

Considering the thermal coefficients of expansion...

- A 10°C temperature variations in Al
  \[= (10\text{C})(2.7\text{e-5 in/in/C}) = 0.00027 = 0.027\%\]
  -or-
  2.7X typical strain

- A 10°C temperature variation in PET
  \[= (10\text{C})(2\text{e-5 in/in/C}) = 0.0002 = 0.02\%\]
  -or-
  0.1X typical strain

Conclusion: Thermal expansion creates much higher stress variations in foils than films.
Summary

- Low strains of foils quickly lead to misalignment angles beyond the critical slack edge angle.
- Handling beyond the critical slack edge angle leads to span interactions (moment transfer).
- Due to slack edges and moment transfer, isolated-span shear wrinkle models are not good predictors of shear wrinkling in wide foils.
- Span interaction (moment transfer) is a detriment to web steering, but should be considered a positive influence in foil handling, opening up a larger wrinkling-free process window than when spans are isolated by high traction.
Based on these results and past experience, the following areas should be considered for the wrinkle-free foil handling:
Unwinding Roll – Coated aluminum rolls are often eccentric (not perfectly centered on the core, shaft, or chucks) and out-of-round. If the span to the first roller is too short, wrinkles will form on the first and second rollers.

Solution: Make the first span long, greater than web width, longer is better.
Summary of Best Practices

- Cylindrical Rollers – Due to the extremely low strain of metal foils, nearly any step change on a roller will create local shear stresses high enough to wrinkle and crease the foil.

  Solution: Remove all tape and contamination from rollers. Use a precision Pi tape to ensure rollers are cylindrical to within 0.01%, especially rubber rollers.
Summary of Best Practices

Roller Level and Tram – Due to the extremely low strain of metal foils, nearly any roller misalignment will create local shear stresses high enough to wrinkle and crease the foil. Shear wrinkles are more likely at higher modulus, wider, thinner foils.

Solution: After ensuring rollers are cylinders, level and tram to better than 0.2 mrad (2 mils/ft, 0.2mm/m).
Summary of Best Practices

- Deflection and Wrap Angles: Foils are extremely sensitive to roller deflection.

✓ Solution: Use rollers with sufficient diameter (e.g. Diameter > Length/10). Reduce deflection from tension with reduced wrap angles. For web path changes over 90-degrees, divide the required re-direction wrap angle between two rollers, reducing deflection due to tension and reducing traction on each roller.
Summary of Best Practices

- Low Tension: Shear wrinkles form through misaligned rollers (or other bending mechanisms), but can be avoided in all webs at either high or low tensions. Foils that are high modulus, thin, and wide are extremely sensitive to all roller errors.

  Solution: Wide foils have a more reasonable wrinkle-free process window at lower tensions.
Summary of Best Practices

- **Displacement and Steering Web Guides:** Even small twisting angles of the displacement guide are enough to create direct or backside wrinkles in the low strain, thin metal foils.

  **Solution:** Work to minimize guiding corrections. Align unwinding roll precisely to process. Prefer sidelay guiding on unwinds and rewinds. If guides can be turned off, ensure servo center position is well-aligned and run in this fixed position.
- Low Friction / Lubrication – Rollers that wrinkle at low speed will often be wrinkle-free at high speed.

✓ Solutions: Air lubrication can greatly reduce the traction force between web and roller and the ability of a roller to bend the web or hold in wrinkles. Lubrication increases with higher speed, low tension, large diameter, and low roughness or limited grooving.

✓ Ideally, wrinkles should not form at low speeds. Seek more robust solutions to eliminate wrinkles that work at all speeds.
Summary of Best Practices

- Downstream of high friction rollers – Wrinkles are more likely to form downstream of nipped and other high traction rollers.

✓ Solutions: Since moment transfer and span interaction can reduce wrinkle sensitivity, locations where moment transfer is unlikely, such as downstream of nipped roller, can be highly wrinkle sensitive. Take special care of spans downstream of high traction roller, such as rubber covered or nipped rollers.
Summary of Best Practices

- **Spreader and Anti-Wrinkle Rollers:** Most spreader rollers are too aggressive for low strain metal foil.

  ✓ **Solution:** Where persistent wrinkles form or downstream of processes with wrinkle-creating mechanics (e.g. heating the foil), use concave roller with radial change of a percent similar to strain of tensioning (less than 0.1%).

  ✓ In some case, herringbone (raised ridges on metal rollers) can pass slightly gathered web without creasing.

  ✓ **Flexible spreaders,** with minimum groove width, can be beneficial for foils above 20 microns, but may leave impressions in thinner foils.
Summary of Best Practices

- **Uniform Temperature**: Due to the low strain and relatively high coefficients of thermal expansion, temperature variations of 10°C (20°F) can be enough to induce wrinkling in metal foils.

  **Solution**: Measure crosweb temperature variations and keep below 5°C (10°F).
Eliminate Nips: Baggy webs and nipped rollers are a common wrinkle cause. Due to the low strain of foils, higher tension may not be able to pull out bagginess and spreader rollers will not stop wrinkles from baggy foil and nips.

Solution: Remove unneeded nipped rollers from all processes. Prefer S-wrap, Omega-wrap, and vacuum-assisted rollers for tension zone separation.
Winding Nip Wrap: 180-degree wrap angles are common on winding nip roller.

Solution: Prefer small 10-20 degrees wrap on winding nip rollers, where possible.
Roll Structure and Roll Handling: Low strain foil wound rolls can easily lose their tension and tightness, becoming soft, buckled, or out-of-round.

Solution: Wind near-core roll layers with high tightness. Taper tension to avoid cinching (and cinching-induced telescoping) and hoop-compression defects (starring, TD buckling). Handle foil wound rolls from the core. Consider winding on spooled cores. Alternately, handling the rolls with a sling or hammock support.
Summary of Best Practices

- Additive effects – Look out for combination of effects.

✓ Solution: Wrinkles are often caused by a combination of effects (e.g. Baggy web running on deflecting, misaligned rollers). Apply as many best practices as possible to open up your wrinkle-free foil handling process window.
Thanks

- Megtec Systems: Foil, $$
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