

<b>Wrinkling of Foils</b>	
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**Extended Abstract:**

Aluminum and copper metal webs less than 150 microns thick (6-mils) are considered foils. In many products, thinner foils have cost or weight advantages, but as with nearly any web, thinner means an increased sensitivity to wrinkling in web handling processes.

Many converters have extensive experience with films and papers, but fear handling foil. This presentation will show experimental results comparing when foil wrinkle vs. papers and films and discuss some of the key points to successful foil handling, especially how foils differ from papers and films.

**Questions of Foil Wrinkling**

- 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?

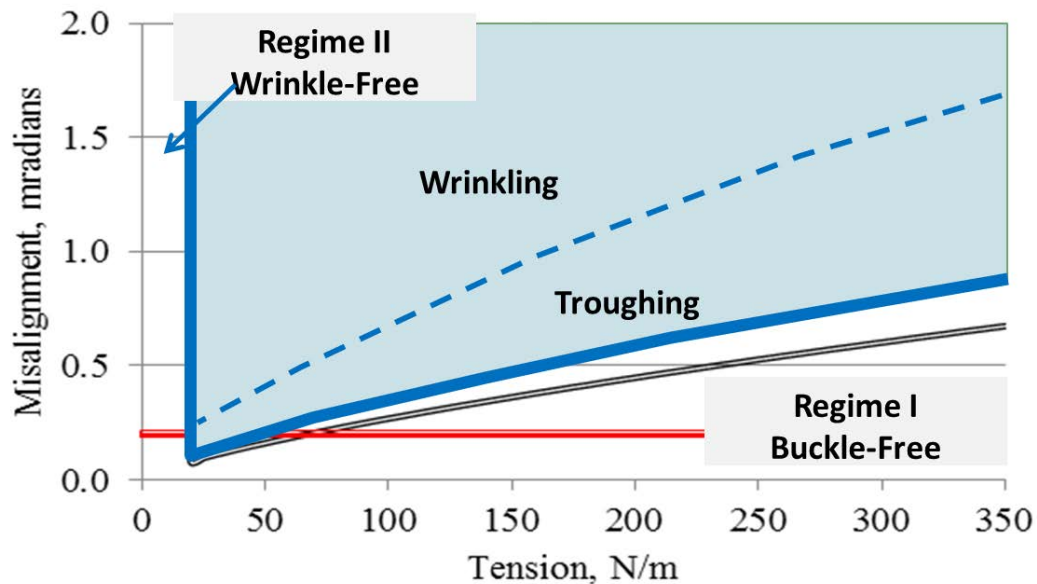
**Comparison of Properties: Aluminum Foil vs. Polyester Film**

In SI units:

	▶ Aluminum Foil	▶ Polyester Film
▶ Elastic modulus of copper and aluminum is 10-20x higher than polyester.	69 <u>GPa</u> (temp. ind.)	3.4-4.8 <u>GPa</u> (temp. dep.)
+ Higher modulus increase stiffness and resistance to buckling – wrinkling.		
- Higher modulus increases stress variations created by roller misalignment		
▶ Yield Stress	140 <u>MPa</u>	140-280 <u>MPa</u> (0.92-0.48 mil)
▶ Yield Strain	0.2%	4-5%
▶ Coefficient of Thermal Expansion	2.7e-5 in/in/C	2e-5 in/in/C
▶ Density	2.8 g/cc	1.4 g/cc
▶ Tear Resistance	Low	Modest-high

In 'English' or American Units:

	▶ Aluminum Foil	▶ Polyester Film
▶ Elastic modulus of copper and aluminum is 10-20x higher than polyester.	10 Mpsi (temp. ind.)	0.5-0.7 Mpsi (temp. dep.)
+ Higher modulus increase stiffness and resistance to buckling – wrinkling.		
- Higher modulus increases stress variations created by roller misalignment		
▶ Yield Stress	21 kpsi	21-41 kpsi (0.92-0.48 mil)
▶ Yield Strain	0.2%	4-5%
▶ Coefficient of Thermal Expansion	13e-6 in/in/F	9e-6 in/in/F
▶ Density	0.0975 lb/in <sup>3</sup>	0.047 lb/in <sup>3</sup>
▶ Tear Resistance	Low	Modest-high



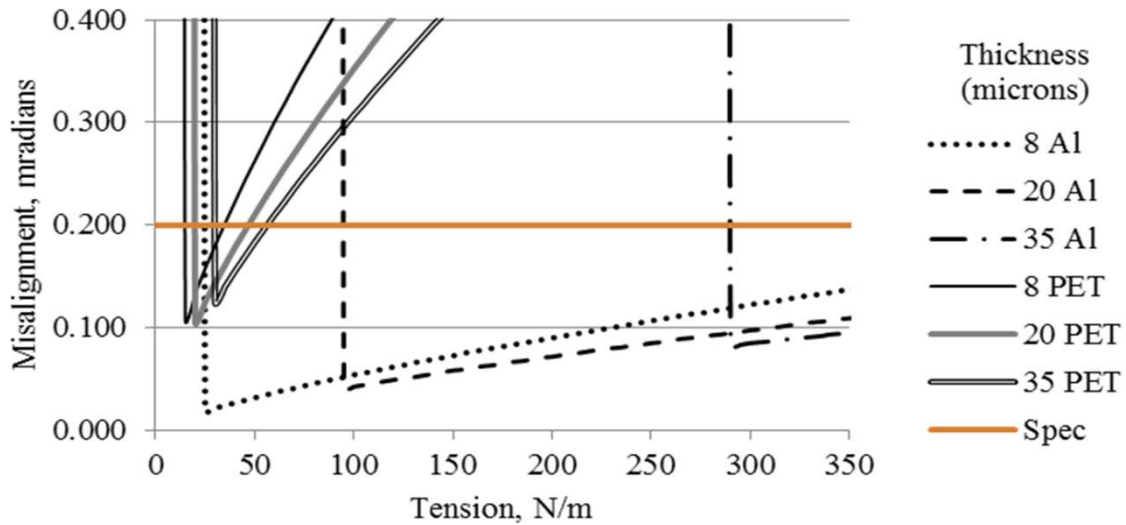
In a typical shear wrinkle plot, there are two transitions from buckle-free and buckling conditions. The first transition, commonly called Regime I, predicts the buckling of the span, what is commonly called troughing [3]. In Regime I the critical angle to form troughing increases with tension or strain due to a tension stiffening effect. The buckling of an isolated span is a direct function of average strain. The high modulus of foils does not provide a stiffness advantage in Regime I buckling sensitivity. For a given tension, the strains and the critical troughing angle will be lower. However, at equal strains, the web geometry (thickness, width, span length) will be the critical factors on when troughs form.

The second transition, Regime II, is a traction limited effect where decreasing tension reduces web-to-roller traction to a point where the roller-applied forces will no longer be able to exceed the web critical buckling stress [3]. Regime II wrinkle-free conditions will expand with thicker webs and lower traction forces. The traction forces between a web and roller are a function of tension (in units of force per width), web width, wrap angle, and coefficient of traction. [Coefficient of traction is a function of coefficient of friction, and lubrication variables of roller diameter, web speed, roller and web roughness, and viscosity of the environmental lubricant whether air or liquid.]

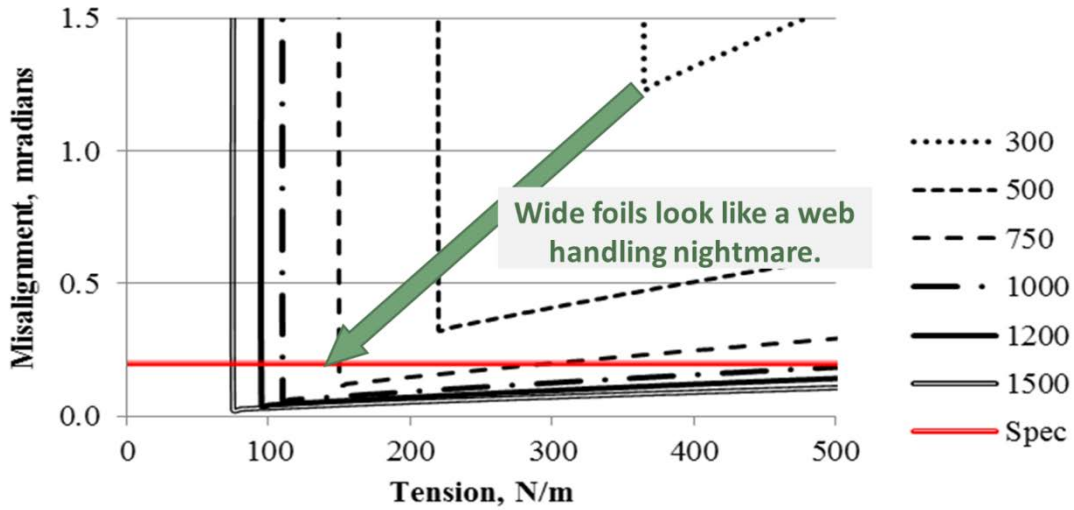
In the isolated-span shear wrinkle model, width will be a strong factor in the Regime II transition. Narrow aluminum or copper will not wrinkle due to insufficient web-roller friction to create the buckling load. However, wide aluminum and copper foils can have sufficient friction to shift Regime II tension, predicting the formation of troughs at small tram angles for typical handling tensions.

Beyond the clear cut theoretical lines of Regime I and II, experimental results often show a rounding or 'knee point' in the tension (or strain) vs. misalignment plots. The shape of this transition zone is not predicted by the Regime I and II models, but can create a significant wrinkle-free zone not predicted by the isolated span model.

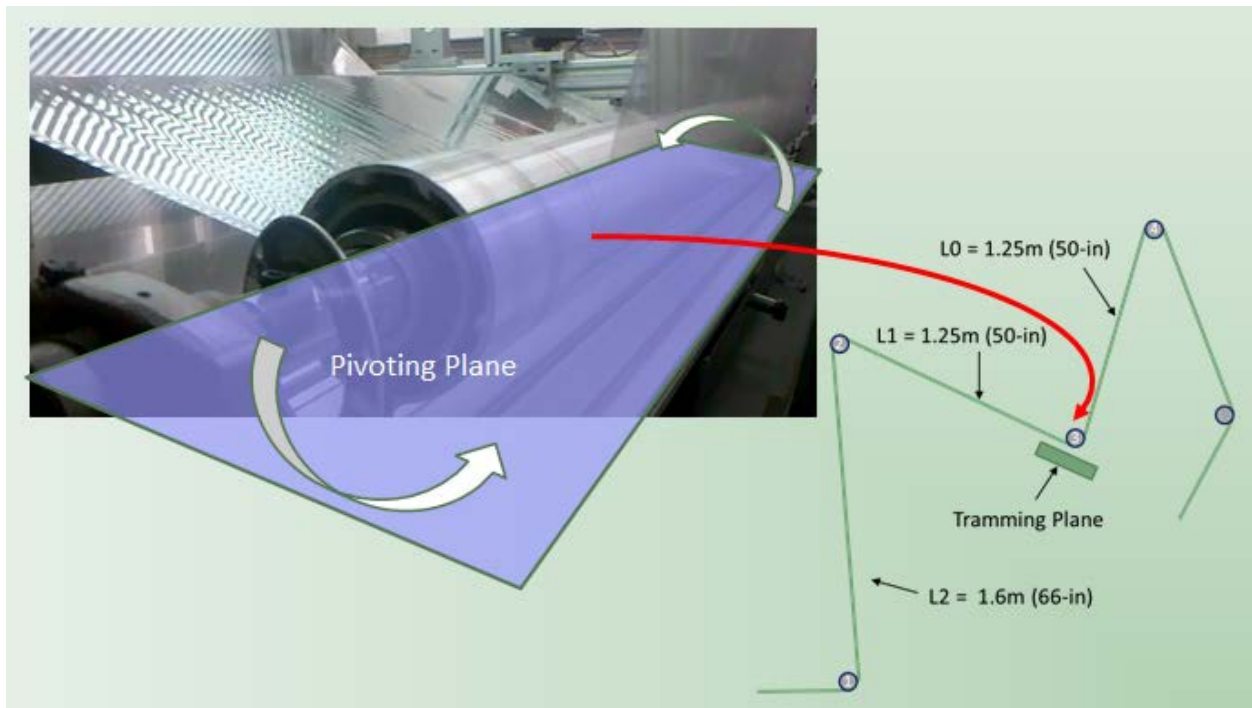
The following graph shows the theoretical conditions where wrinkles will form in aluminum and polyester webs as a function of tension, misalignment, and thickness. Note: Aluminum foils have a much more dramatic increase in shear wrinkle sensitivity as a function of thickness.



For 20 micron aluminum foil, increasing width dramatically changes the theoretical sensitivity to roller misalignment. Wider webs have more ability to create the lateral force and stress required to reach the buckling criteria.

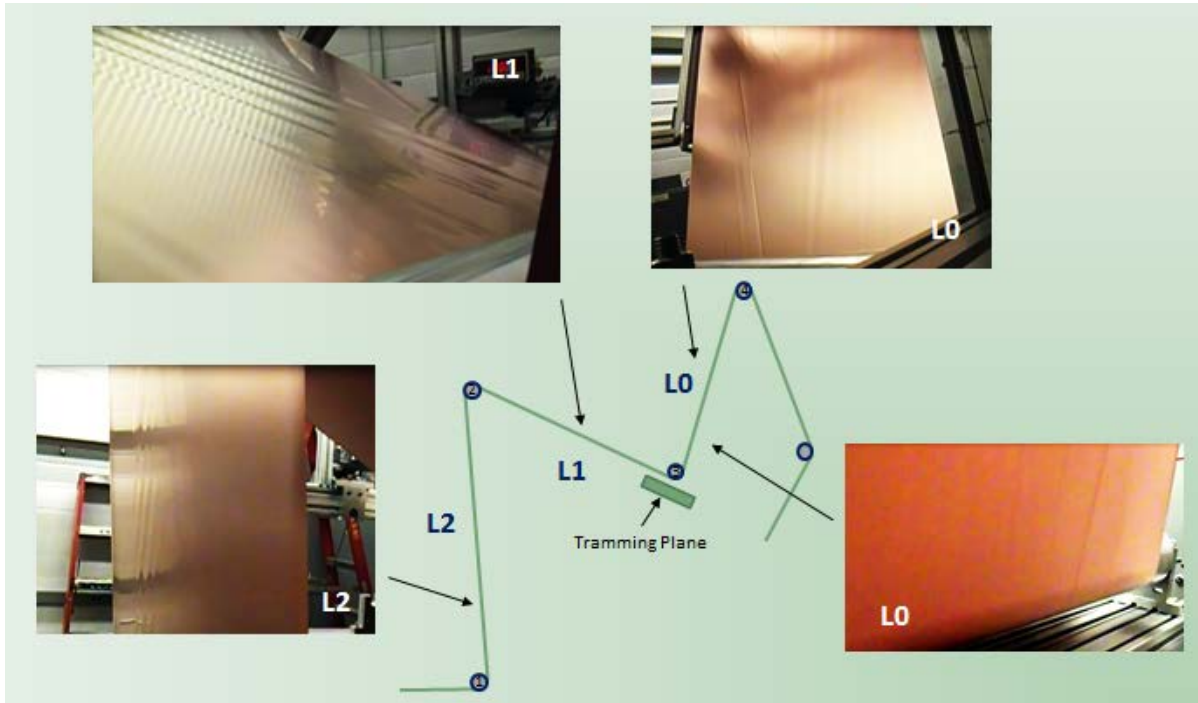


The following diagram and photo show our experimental setup. Spans L2, L1, and L0 are the two spans before and the one span after our target controlled misalignment roller, respectively.

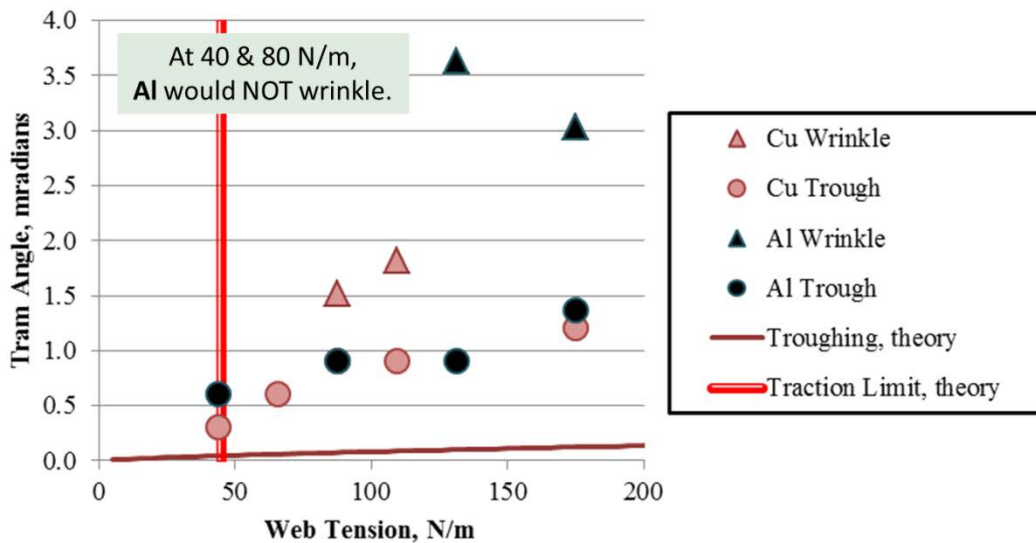


Surprisingly, the thin copper foil formed wrinkles on three different rollers from three different wrinkling mechanisms. On our target (intentionally misaligned) roller, at the end of our L1 span, the copper foil wrinkles from created classic misalignment-induced shear wrinkles. On the roll upstream of our target roller, between spans L1 and L2, the copper foil formed a 'backside' shear wrinkle, created when the crossweb tension variations from the target roller's

misalignment slipped over the upstream roller and induce shear wrinkles in span L2. Lastly, due to the long span, large wrap angle, and small diameter of the roller after our target roller (at the end of span L0), the copper wrinkles from roller deflection, creating tracking or gathering wrinkles.



The graph below shows the combined tension and misalignment conditions that formed troughs and wrinkles in 20 micron (0.8-mil) aluminum and 12 micron (0.5-mil) copper foils, both 1.2m wide (48-in). Note: At low tensions, 40 and 80 N/m (0.25 and 0.5 PLI), the 20 micron aluminum would NOT wrinkle.



## DETAILS ON SLACK EDGE AND MOMENT TRANSFER

Slack edges begin when angle of misalignment x web width is greater than span length x strain.

$$\theta W > L \epsilon$$

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 BUCKLING FROM ROLLER MISALIGNMENT AND DEFLECTION

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

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.**

**Buckling criteria of the on-roller web does not predict that foil would be more sensitive to roller deflection, but experience shows thin foils are much more sensitive to this mechanism than polyester films. The in-span buckling criteria that is proportional to the square root of strain would make high straining films less wrinkle sensitive than foils.**

## DETAILS ON STRAIN AND TEMPERATURE VARIATIONS

Considering the thermal coefficients of expansion...

A 10C temperature variations in Al = (10C)(2.7e-5 in/in/C) = 0.00027 = 0.027%

-or- 2.7X typical strain

A 10C temperature variation in PET = (10C)(2e-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.

### FOIL HANDLING BEST PRACTICES

Foils that are high modulus, thin, and wide are extremely sensitive to all roller errors.

Based on these results and past experience, review and consider all the following areas to achieve wrinkle-free foil handling:

Foil Wrinkling Causes / Concerns	Solutions
<p><b>Unwinding Roll</b> – 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.</p>	<p>Make the first span long - greater than web width, longer is better.</p>
<p><b>Cylindrical Rollers</b> – 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.</p>	<p>Remove all tape and contamination from rollers. Use a precision Pi tape to ensure rollers are cylindrical to within 0.01%, especially rubber rollers.</p>
<p><b>Roller Level and Tram</b> – 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.</p>	<p>After ensuring rollers are cylinders, level and tram to better than 0.2 mradians (2 mils/ft, 0.2mm/m).</p>
<p><b>Deflection and Wrap Angles</b> – Foils are extremely sensitive to roller deflection.</p>	<p>Use rollers with sufficient diameter (e.g. Diameter &gt; 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.</p>

Foil Wrinkling Causes / Concerns	Solutions
<p><b>Low Tension</b> – Shear wrinkles form due to bending induced by misaligned rollers (or other bending mechanisms), but in borderline cases, can be avoided in all webs at either high or low tensions.</p>	<p>Wide foils have a more reasonable wrinkle-free process window at lower tensions.</p>
<p><b>Displacement and Steering Web Guides</b> – Even small twisting angles of the displacement guide are enough to create direct or backside wrinkles in the low strain, thin metal foils.</p>	<p>Work to minimize guiding corrections. Align unwinding roll precisely to process. Prefer sidelay guiding on unwinds and rewinds, shifting the entire winding stations laterally to present the web on centerline (unwinding) or position the winder core on centerline with the incoming web (winding), over displacement or steering guides that rely on twisting and bending the web. If guides can be turned off, ensure servo center position is well-aligned and run in this fixed position.</p>
<p><b>Low Friction / Lubrication</b> – Rollers that wrinkle at low speed will often be wrinkle-free at high speed.</p>	<p>Air lubrication of air entrained with the moving web and spinning roller can greatly reduce the traction force between web and roller and the ability of a roller to bend the web or hold the web in a wrinkled shape. 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.</p>
<p><b>Spreader and Anti-Wrinkle Rollers</b> – Most spreader rollers are too aggressive for low strain metal foil.</p>	<p>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.</p>
<p><b>Uniform Temperature</b> – Due to the low strain and relatively high coefficients of thermal expansion, temperature variations of 10C (20F) can be enough to induce wrinkling in metal foils.</p>	<p>Measure MD temperature variations and keep below 5C (10F).</p>



Foil Wrinkling Causes / Concerns	Solutions
<p><b>Eliminate Nips</b> – 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.</p>	<p>Remove unneeded nipped rollers from all processes. Prefer S-wrap, Omega-wrap, and vacuum-assisted rollers for tension zone separation.</p>
<p><b>Winding Nip Wrap</b> – 180-degree wrap angles are common on winding nip roller.</p>	<p>Prefer small 10-20 degree wrap on winding nip rollers, where possible, or nipping after the initial contact point.</p>
<p><b>Roll Structure and Roll Handling</b> – Low strain foil wound rolls can easily lose their tension and tightness, becoming soft, buckled, or out-of-round.</p>	<p>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.</p>